Constraints on axions from massive stars

Maurizio Giannotti, *Barry University*

(Mostly) Based on:
Phys.Rev.Lett. 110 (2013) 061101
with A. Friedland and M.Wise

INFO 2013,
Santa Fe, August 2013

Outline

- Stars and particle physics
- Axion and Axion-Like Particles (ALPs)
- Cast and the Horizontal Branch bounds on the axion-photon coupling
- Bound on the axion-photon coupling from massive stars
- Conclusions

Stars as Laboratories

For 50 years stars have been excellent laboratories for light, weakly interacting particles. In fact, stars are sensitive to very rare processes, e.g.,

$$\gamma \to \nu + \bar{\nu}$$

and

$$e^+ + e^- \to \nu + \bar{\nu}$$

which are extremely rare but play a fundamental role in stellar cooling.

Examples of models strongly constrained by stars include <u>majorons</u>, <u>extra-dimensional photons</u>, <u>novel baryonic or leptonic forces</u>, <u>unparticles</u>, etc.

J. Bernstein et al., Phys. Rev. 132, 1227 (1963)

H.M. Georgi, S.L. Glashow, and S. Nussinov, Nucl. Phys. B193, 297 (1981)

A. Friedland and M. Giannotti, Phys. Rev. Lett. 100, 031602 (2008)

Grifols and E. Masso, Phys. Lett. B 173, 237 (1986)

S. Hannestad, G. Raffelt, and Y.Y.Y. Wong, Phys. Rev. D76, 121701 (2007)

A considerable improvement in astrophysical observations is now leading to revision and improvement of stellar bounds

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Recently, Raffelt and collaborators have been revising the old stellar bounds on neutrino magnetic moment and axion–electron coupling, providing more reliable bounds which include confidence levels.

[*N. Viaux et. al. 2013, N. Viaux, Ph.D. thesis*]

Wong, Phys. Rev. D76, 121701 (2007)

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The case of the Axion

A particularly interesting example of light, weakly interacting particle is the **axion**, hypothetical particle whose existence is a prediction of the Peccei-Quinn solution of the Strong CP problem:

Peccei and Quinn (1977),
Weinberg (1978),
Wilczek (1978)

QCD has a CP-violating term:

$$\boxed{L_{CP} = \frac{g^2}{32\pi^2}\Theta\, G\widetilde{G}}$$

which has the observable effect of generating an electric dipole moment

$$\boxed{d_n \approx \Theta\, 10^{-16}\, e\ \mathrm{cm}}$$

Baluni (1979), Crewther, Vecchia, Veneziano, Witten(1979)

Naturally, one would expect Θ=1.
However, the neutron's electric dipole moment is not observed and experiments show that

$$\Theta < 10^{-10}$$

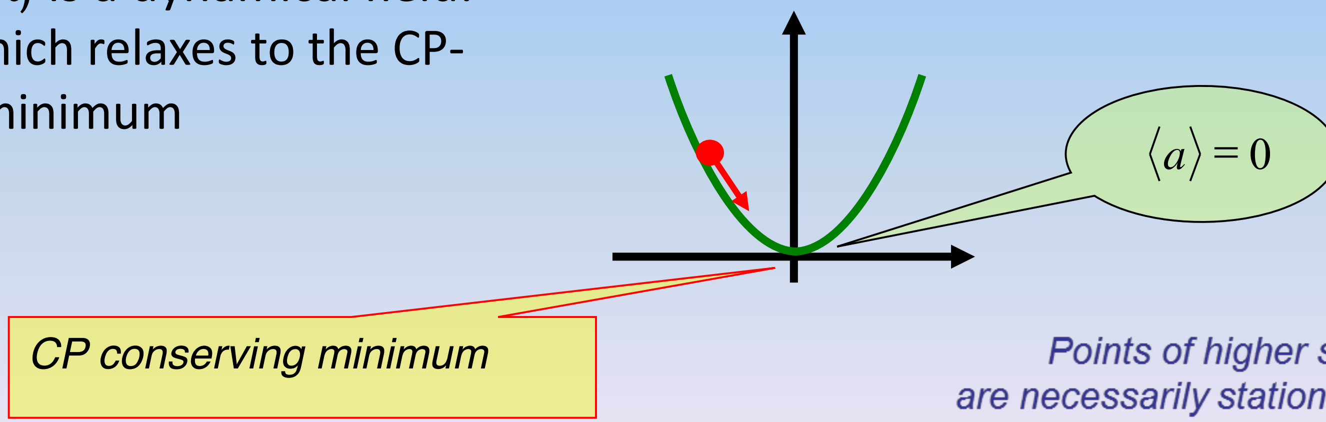
The case of the Axion

The problem is solved if the CP-violating term is substituted with

Peccei and Quinn (1977),
Weinberg (1978),
Wilczek (1978)

$$L_\Theta \rightarrow L_a = \frac{1}{2}\partial_\mu a\,\partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a}\; G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Where f_a is the Peccei Quinn mass scale and $a(x)$ is a dynamical field: the **axion** which relaxes to the CP-conserving minimum



Points of higher symmetry are necessarily stationary points (Weinberg)

Axion and Axion-Like Particles (ALPs)

Besides being a prediction of the most appealing solution of the strong CP problem, axions are prominent dark matter candidate.

Preskill, Wise and Wilczek (1983)
Abbott and Sikivie (1983)
Dine and Fischler (1983)

In the *standard* (QCD) *axion models* the axion interaction with matter and photons and the axion mass are related through the Peccei-Quinn constant f_a

$$L_{\mathrm{int}} = -i\frac{C_i m_i}{f_a} a\overline{\psi}\gamma_5\psi - \frac{1}{4} g_{a\gamma} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Axion-photon coupling

$$m_a \approx \frac{6\,\mathrm{eV}}{f_a/10^6\,\mathrm{GeV}}$$

$$g_{a\gamma} = \xi \frac{\alpha_{em}}{2\pi f_a}$$

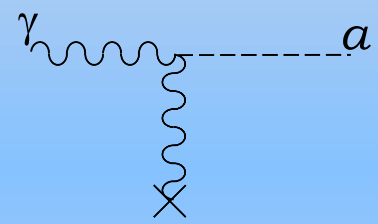
However, one can construct more general models for Axion-Like Particles (**ALPs**), whose couplings and the mass are unrelated.

Axions and Stellar Evolution

Light ALPs can be produced in stars through various mechanisms, e.g.

Primakoff conversion

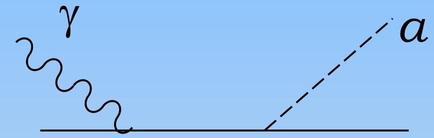
$$\gamma + Ze \rightarrow a + Ze$$



Relevant in He-burning stars

Compton scattering

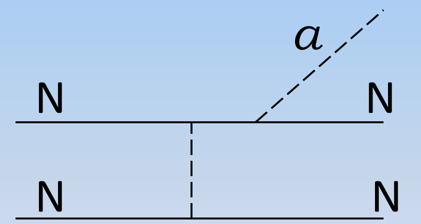
$$\gamma + e \rightarrow a + e$$



Relevant in RG and WD

Nucleon Bremsstrahlung

$$N + N \rightarrow N + N + a$$



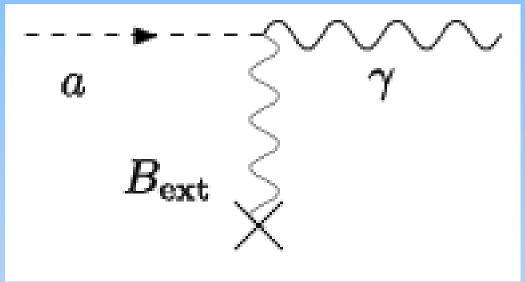
Relevant in SN and neutron stars

The emission of axions could lead to an *overly efficient energy drain*, inconsistent with observations. This leads to bounds on the axion couplings with photons, electrons and nuclei.

Axion detection: the role of the Axion-Photon Coupling

Most of the modern axion searches are based on the microwave cavity detection proposed by P. Sikivie, which relays on the axion-photon coupling. Axions can be converted into photons in an external magnetic filed. These bounds depend on the axion mass.

P. Sikivie, Phys.Rev.Lett. 51, 1415 (1983)



Axion-photon vertex

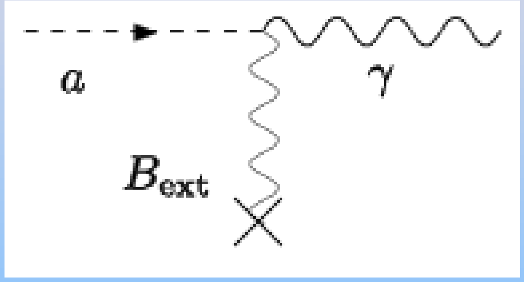
A strong terrestrial bound on the axion (ALPs)-photon coupling comes from the Cern Axion Solar Telescope (**CAST**)

$$g_{a\gamma} \leq 0.88\times10^{-10}\mathrm{GeV}^{-1}$$

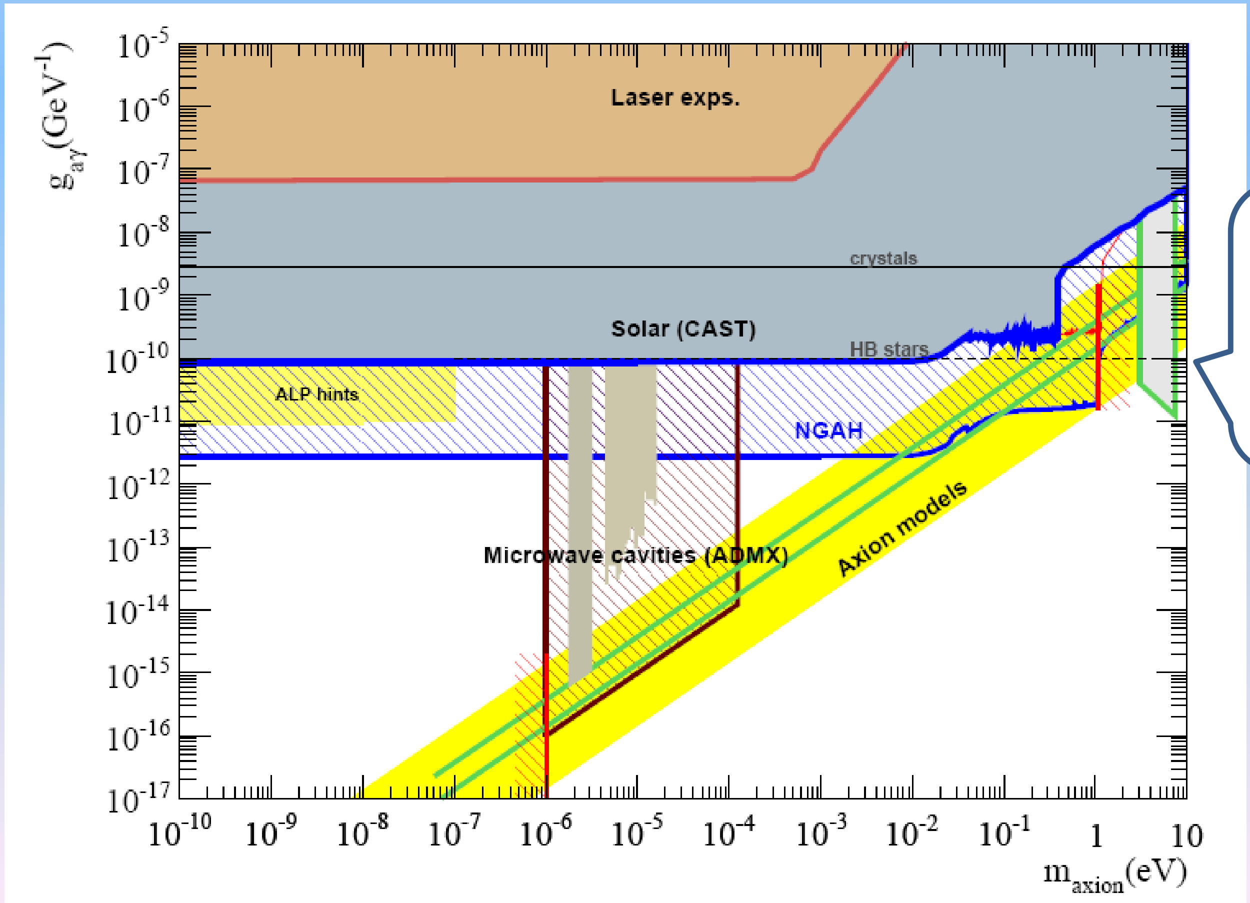
The bound is however weakened at masses >0.02eV (in the QCD –axion region)

Experimental Axion (and ALPs) Search

CAST and ADMX provide the strongest bound on the axion-photon coupling. The Next Generation Axion Helioscopes (NGAH) are expected to improve the bounds by over an order of magnitude.



Axion-photon vertex



HB-bound, g_{10}=1.

Raffelt and Dearborn PRD 36 (1987)

From Biljana Lakić, CAST, PATRAS 2013, Mainz

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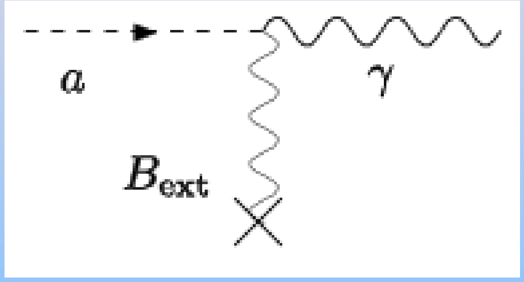

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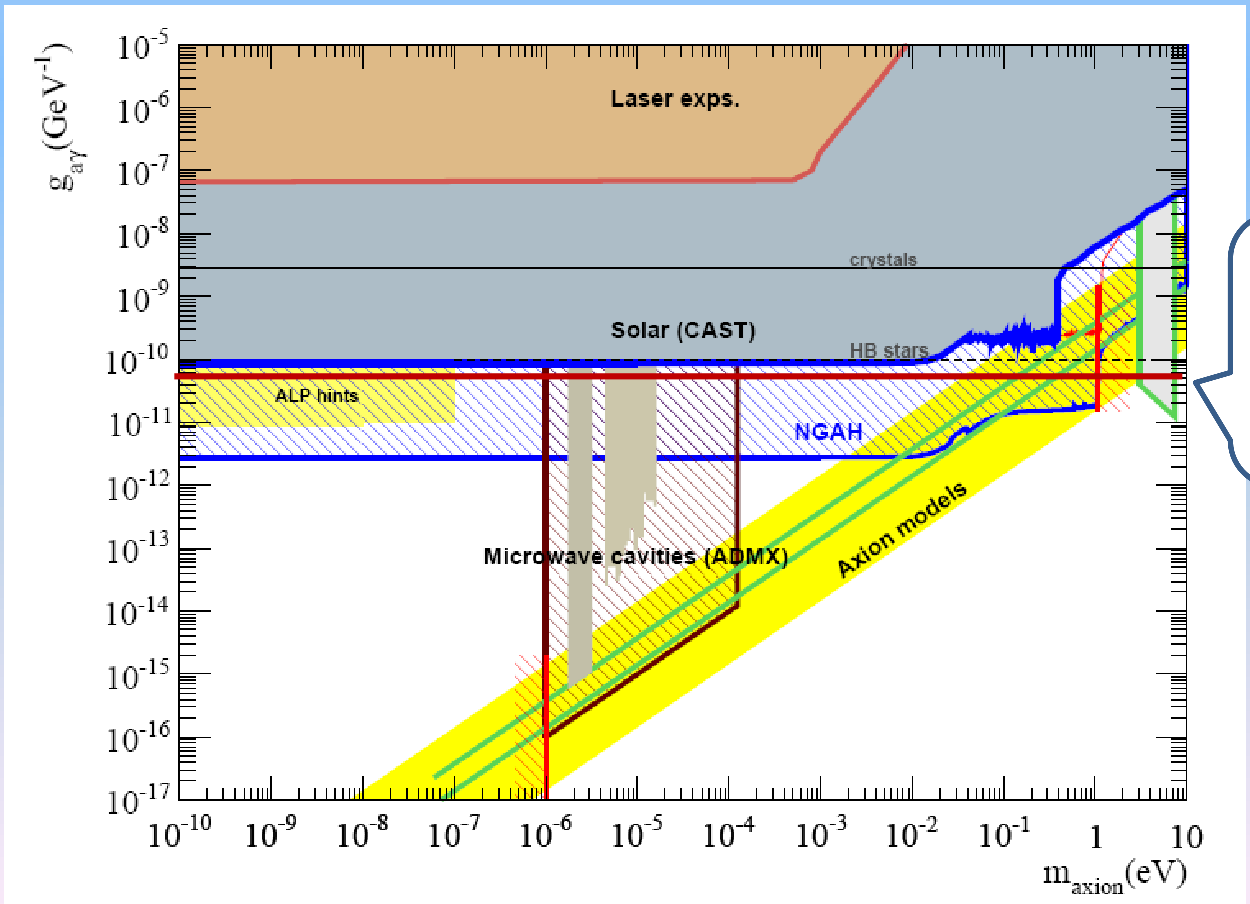


Massive stars-bound,
$g_{10}=0.8$

A.Friedland, M.G., M.Wise, **PRL 110 (2013)**

From Biljana Lakić, CAST, PATRAS 2013, Mainz

Experimental Axion (and ALPs) Search: CAST

- **Vacuum Phase**

  $$m_a \leq 0.02\, eV$$

  → $g_{a\gamma}$ (95%) < 0.88 x 10^{-10} GeV^{-1}
  → Phys.Rev.Lett.94:121301, 2005
  → JCAP 04 (2007) 010

- **^{4}He Phase**

  $$0.02\, eV \leq m_a \leq 0.39\, eV$$

  → g_{ag} (95%) < 2.2 x 10^{-10} GeV^{-1}
  → JCAP 02 (2009) 008

- **^{3}He Phase: first results**

  $$0.39\, eV \leq m_a \leq 0.65\, eV$$

  → $g_{a\gamma}$ (95%) < 2.3 x 10^{-10} GeV^{-1}
  → Phys.Rev.Lett. 107:261302, 2011

- **^{3}He Phase: preliminary results**

  $$0.65\, eV \leq m_a \leq 1.18\, eV$$

  → Publication in preparation

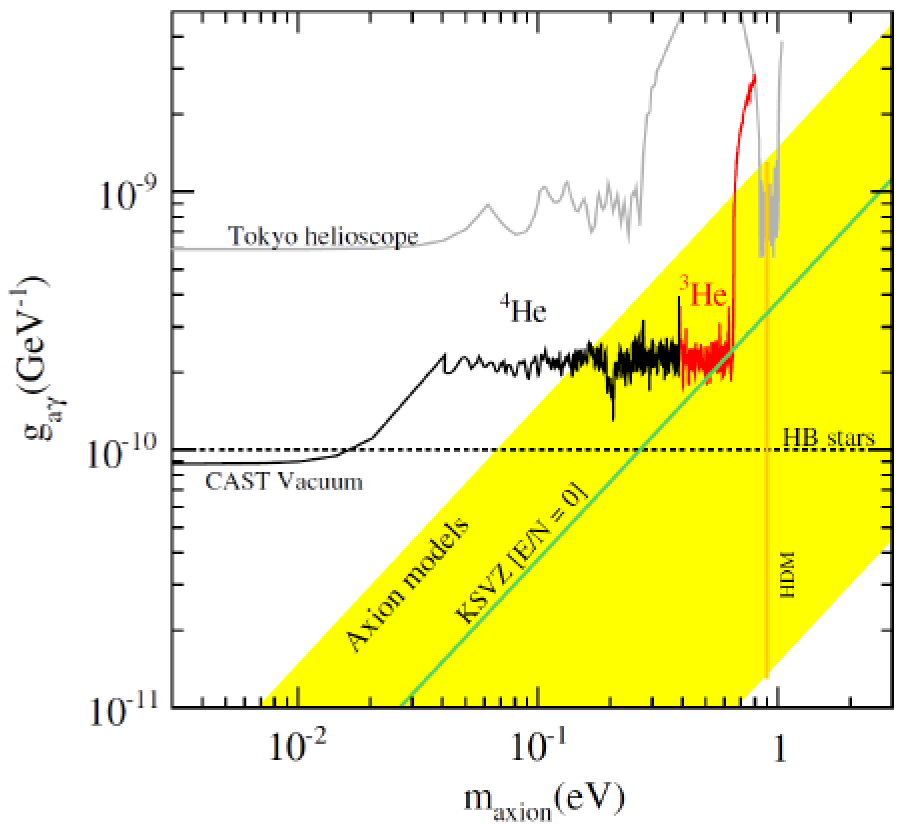
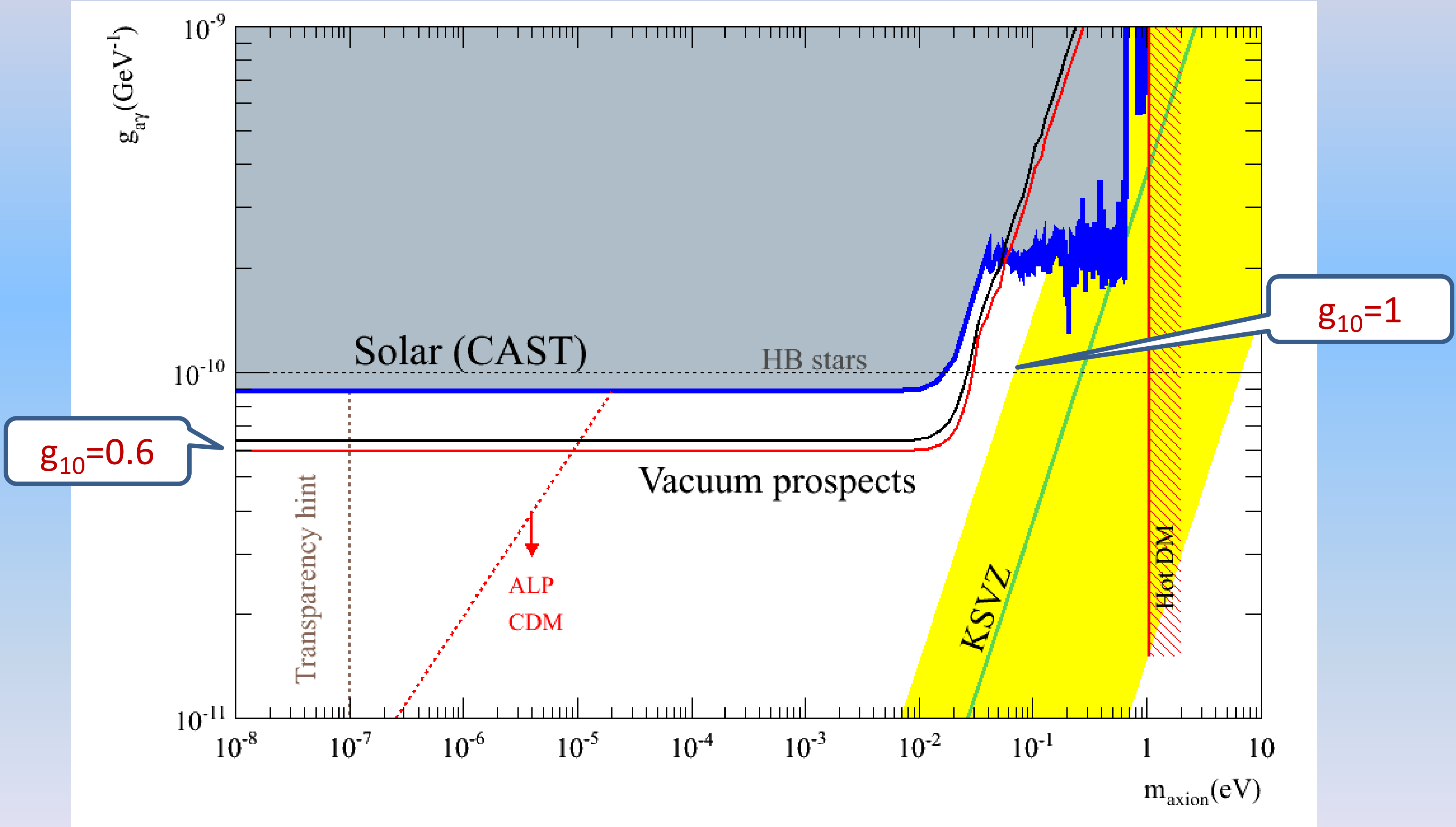


Image and data from Julia Vogel (LLNL), CAST

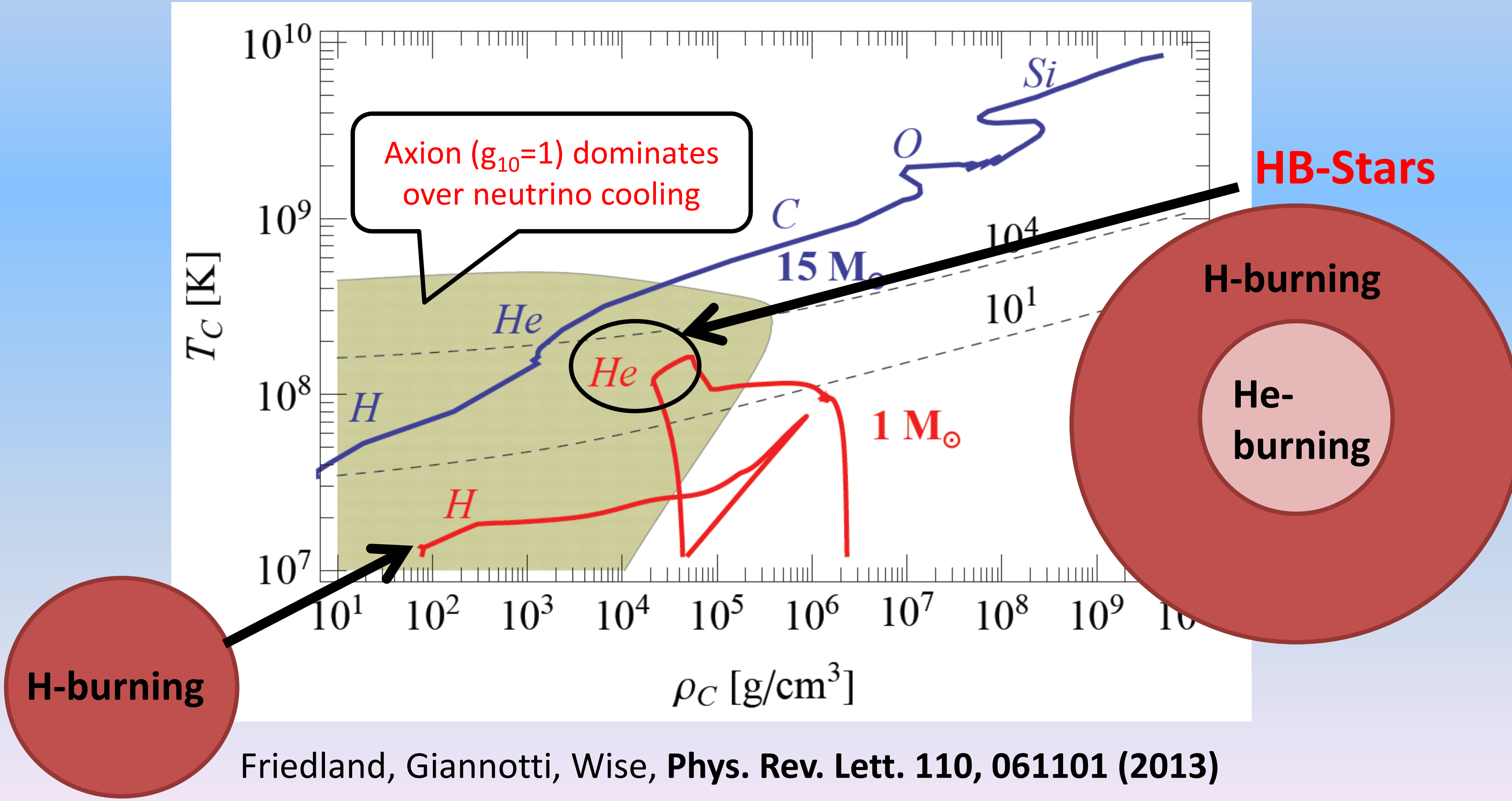
Experimental Axion (and ALPs) Search: CAST



From Biljana Lakić, CAST, PATRAS 2013, Mainz

The HB bound on the axion-photon Coupling

Axions can be produced in the core of a star from photons interacting with the electric field of the nuclei (**Primakoff process**).



Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

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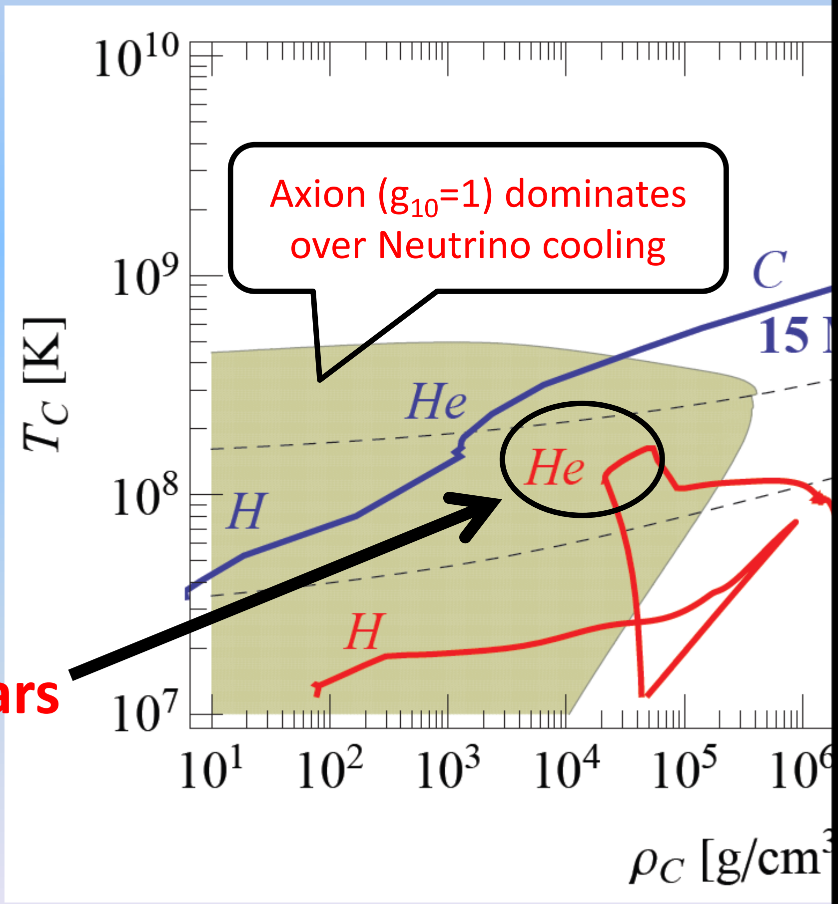


HB-Stars

Friedland, Giannotti, Wise, **Phys. Rev.**

Axions coupled too strongly to photons would speed up the consumption of He in the HB star core and reduce the HB lifetime.

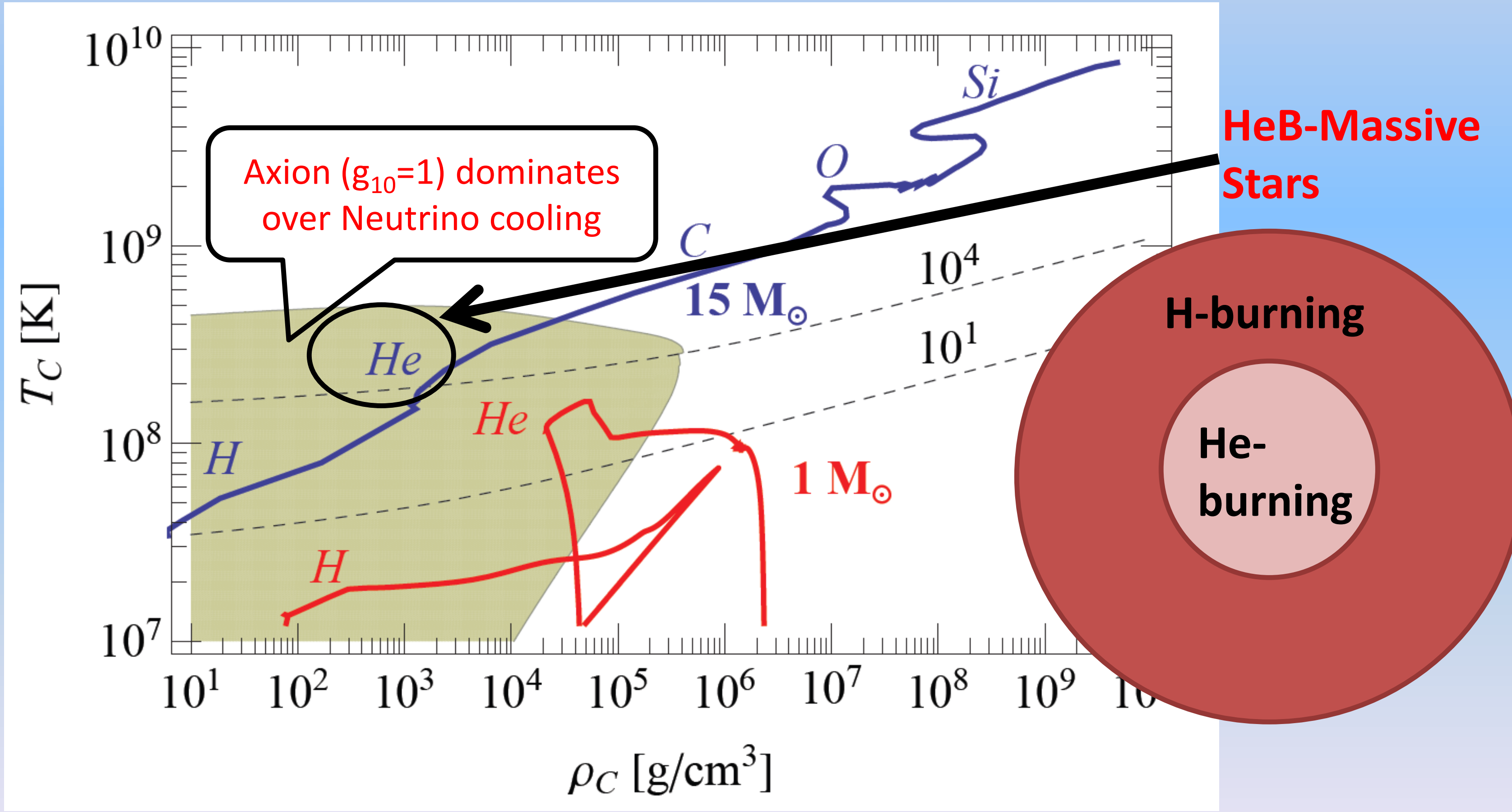
Observational constrains come from the comparison of the number of HB vs. RG stars.

The bound $g_{a\gamma} \leq 10^{-10}\mathrm{GeV}^{-1}$ [G.G. Raffelt and D.S.P. Dearborn, **Phys. Rev. D36, 2211(1987)**] (which is the one currently reported in the PDG) corresponds to a reduction of the HB star lifetime by 30%.

The bound applies to axion masses <30 keV or so.

Axion and He-burning massive stars

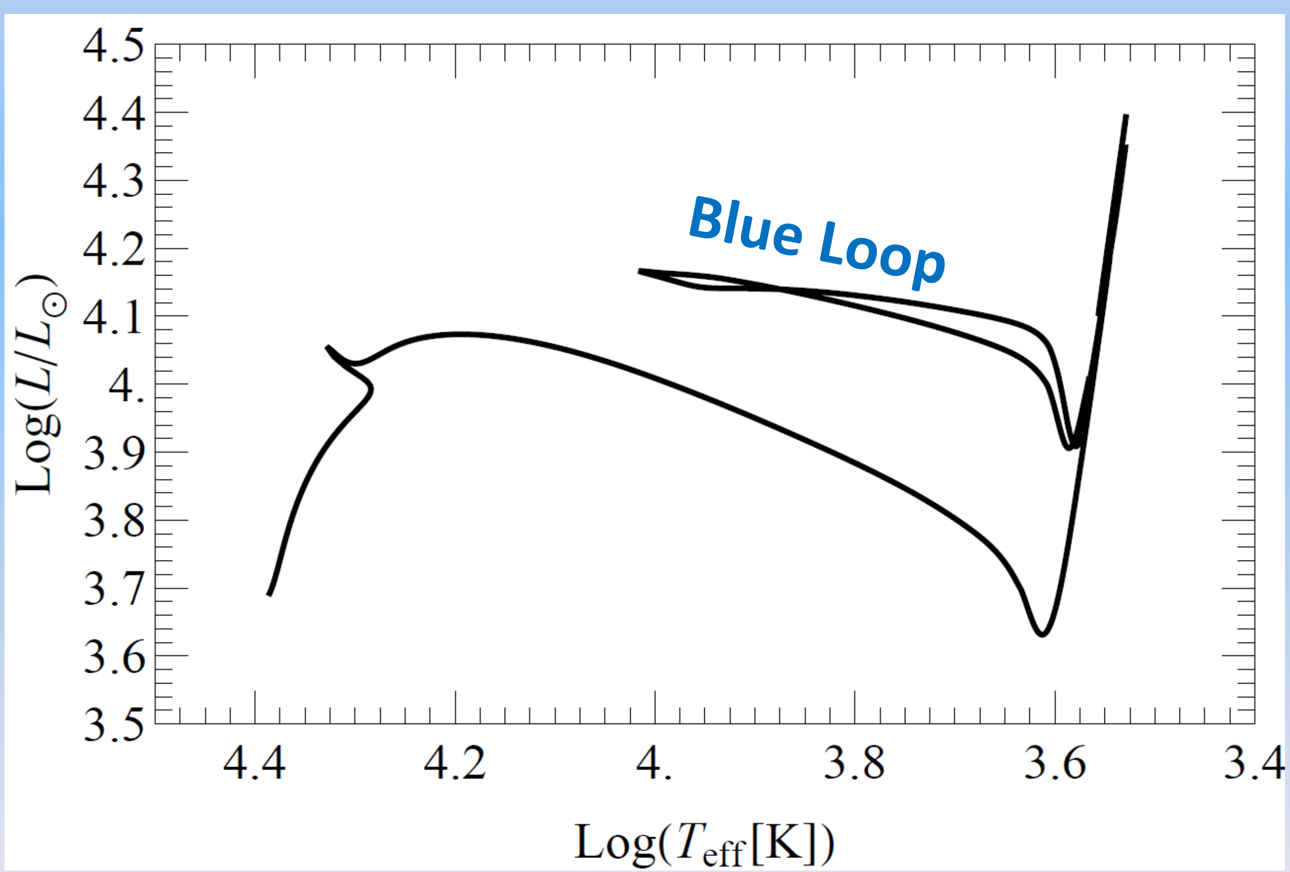
However, the currently strongest bound on the axion-photon coupling comes from the analysis of the evolution of He-burning massive stars



Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

The Blue Loop

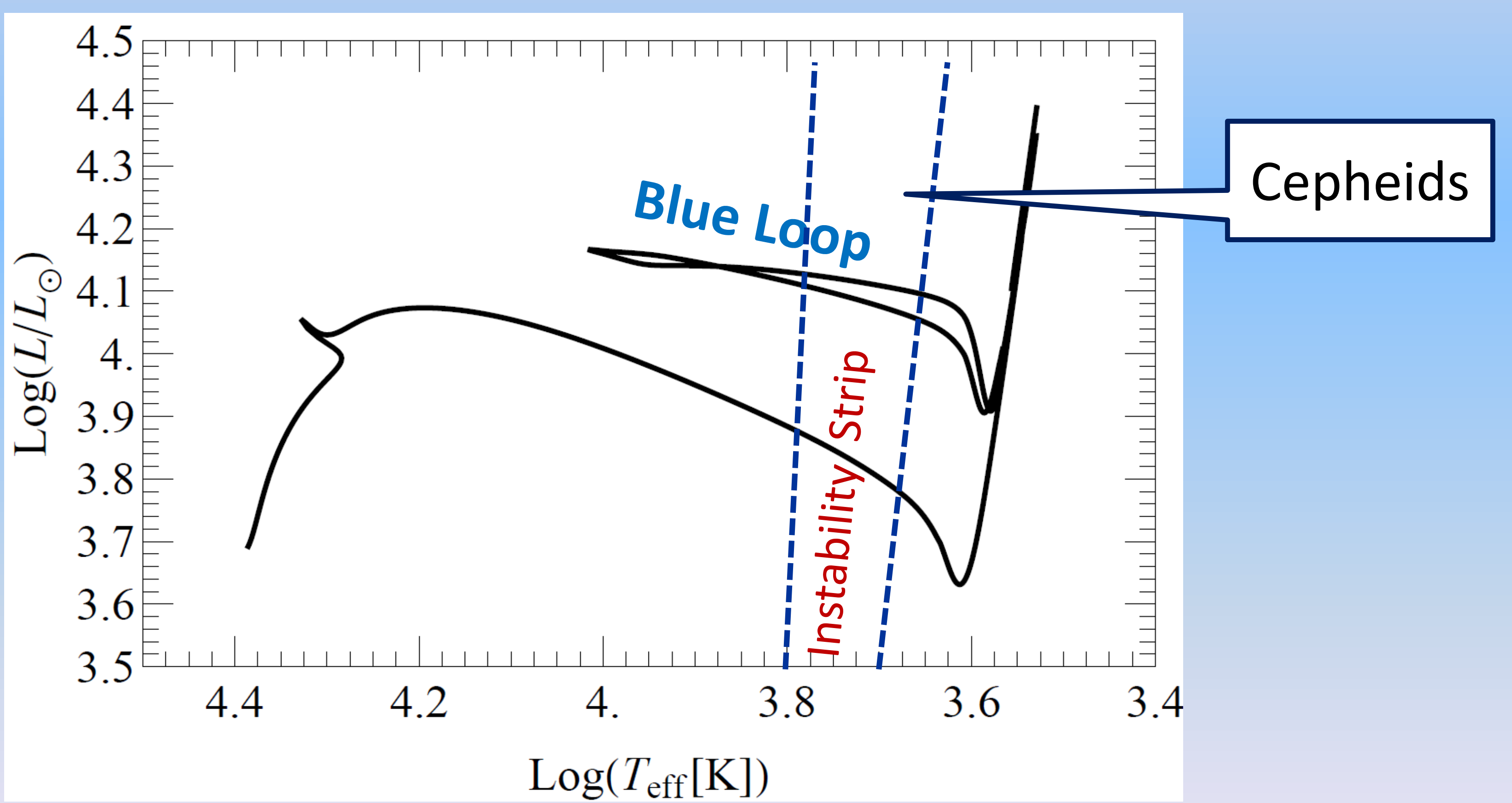
The HR diagram shows the luminosity vs. surface temperature of a star.
The **blue loop** is a prominent feature of the evolution of a massive star.



Simulations for a $9.5\mathrm{M}_\odot$, solar metallicity, from main sequence to end of He-burning.
MESA (Modules for Experiments in Stellar Astrophysics), Paxton et al. *ApJ Suppl*. **192** 3 (2011) [arXiv:1009.1622]

The Blue Loop and the Cepheids

The blue loops are necessary to explain the existence of the Cepheids



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Cepheids in a nutshell

Cepheids, also called Cepheid Variables, are stars which brighten and dim periodically.

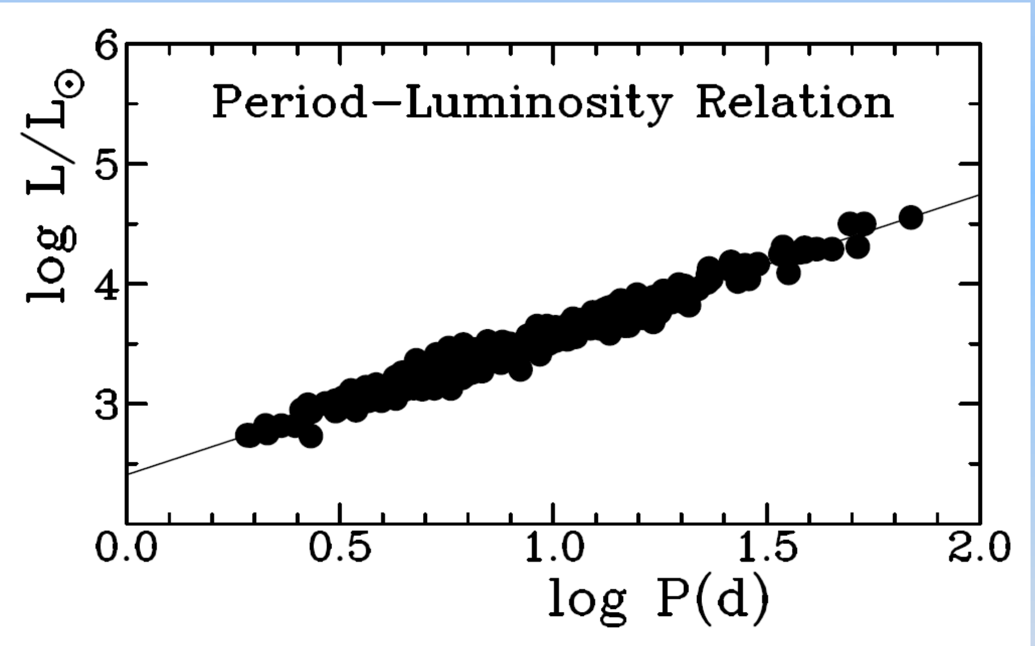
The luminosity and the periods are related as:

$$\log L/L_{\odot} = 2.409 + 1.168 \log P$$

The periods are about 1-50 days.

The strip extends for a narrow temperature interval and for luminosities from 300–30,000 $L_{\odot}$.

The variation in brightness can be up to a factor of 3.



D. Turner et al. (2011) *"The period-luminosity relation defined by Cepheids of well-established reddening"*.

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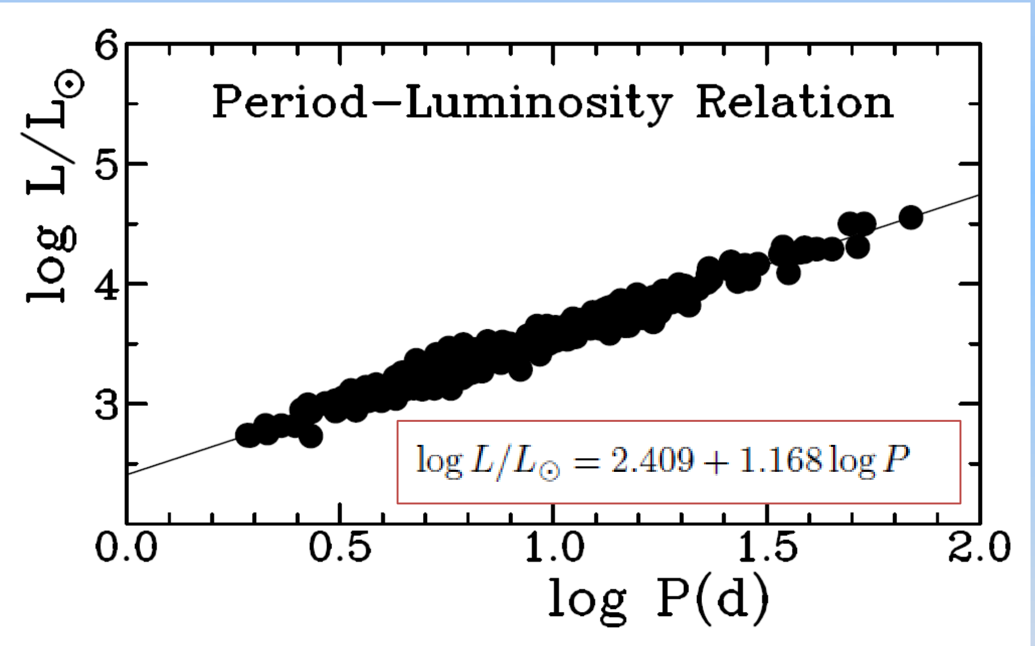
The Period-Luminosity Law was discovered by Henrietta Leavitt in 1912 and explained with the κ-mechanism by Sir Arthur Eddinghton in 1916:

At the dimmest part of a Cepheid's cycle, the helium is doubly ionized and therefore more opaque. So, the gas is heated by the star's radiation, and begins to expand. As it expands, it cools, it becomes less ionized and more transparent, allowing the radiation to escape.



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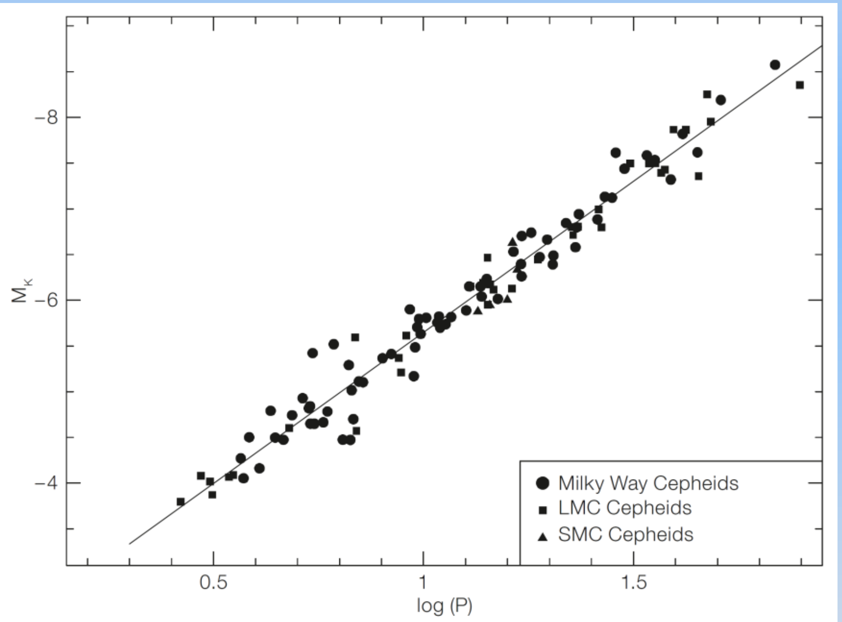
Cepheids are abundant and very bright. Astronomers can identify them not only in our Galaxy but also in other nearby galaxies.

The figure shows recent observations from the Milky Way, the Large and the Small Magellanic Cloud.

GAIA (Global Astrometric Interferometer for Astrophysics) is expected to improve considerably the observation of Cepheids.



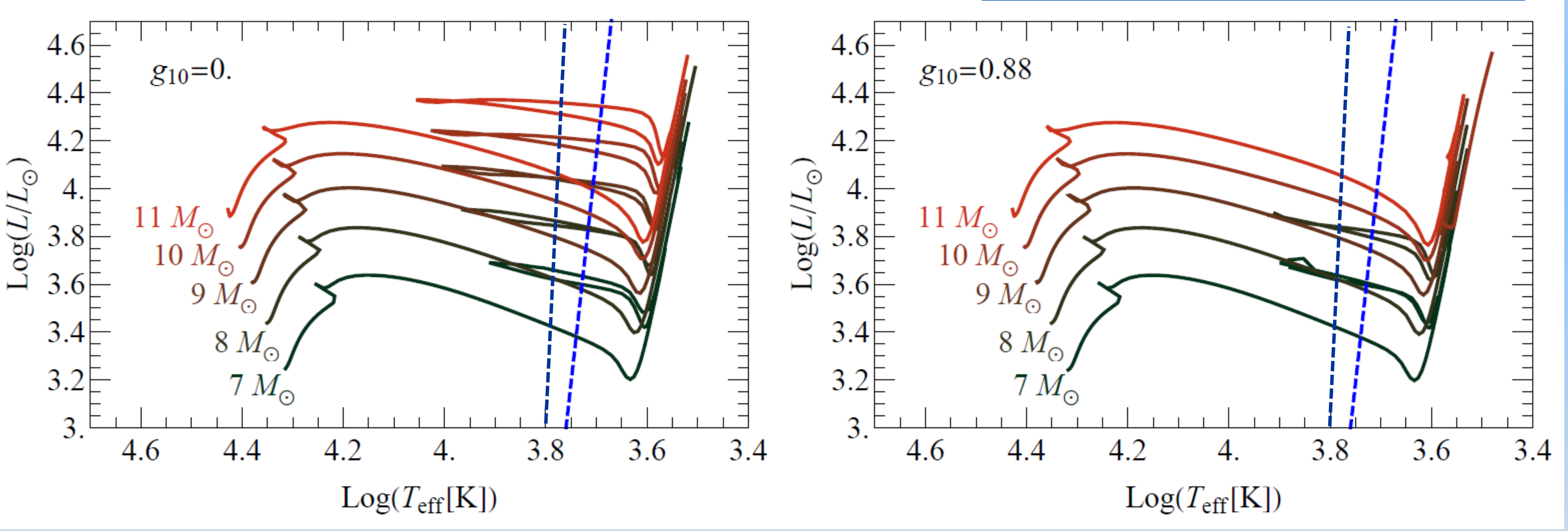
Jesper Storm et al. (2012)

The dispersion is about 0.22 mag and is dominated by distance errors from the analysis.

Axions effects on the Blue Loop

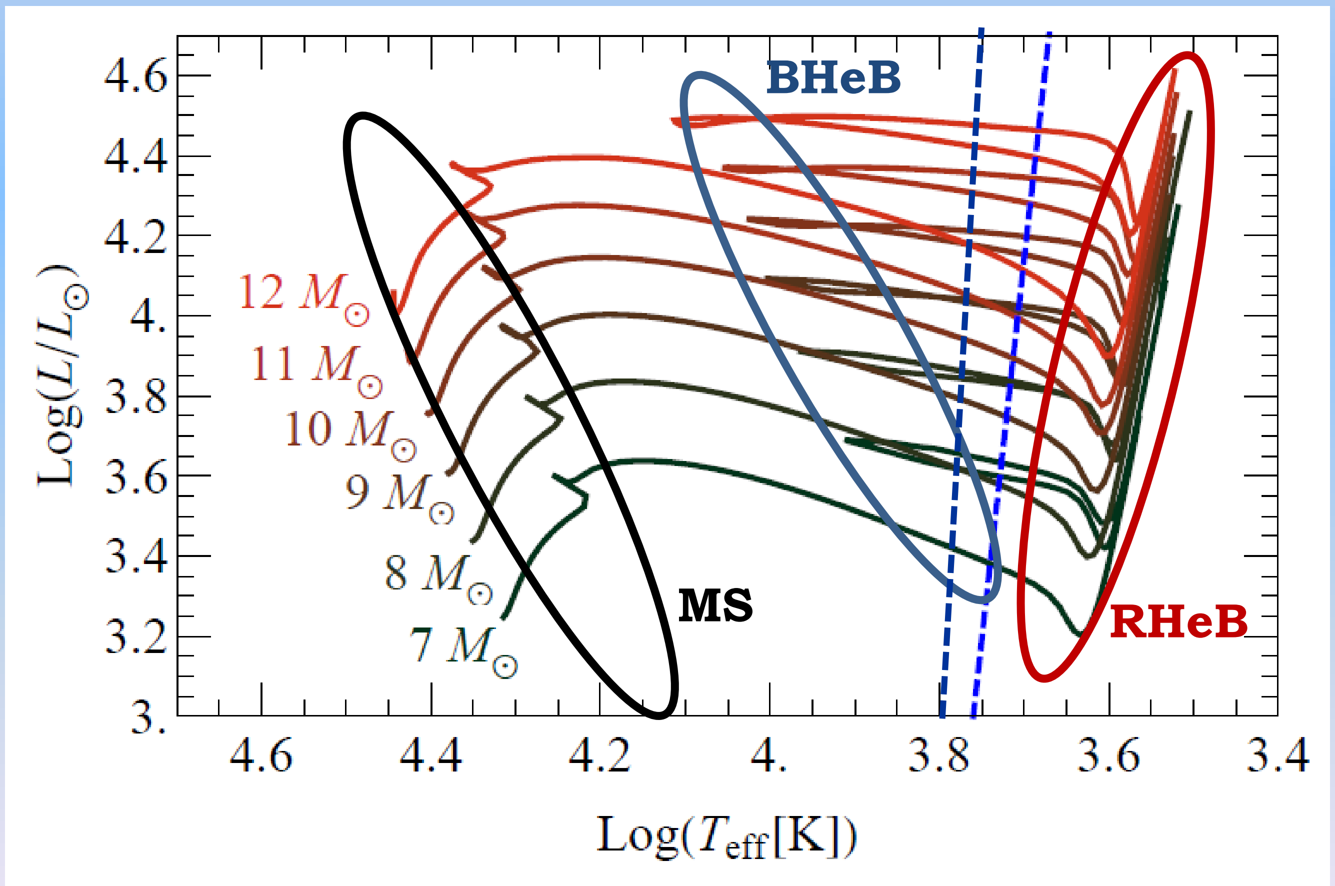
The value g_{10}=0.88 corresponds to the current CAST bound on the axion-photon coupling.

A.Friedland, M.G., and M.Wise,
Phys. Rev. Lett. 110, 061101 (2013)



A value of g_{10}=0.8 would provide qualitative changes in the stellar evolution. In particular, it would eliminate the blue loop stage of the evolution, leaving one without an explanation for the existence of Cepheid stars in a broad range of pulsation periods.

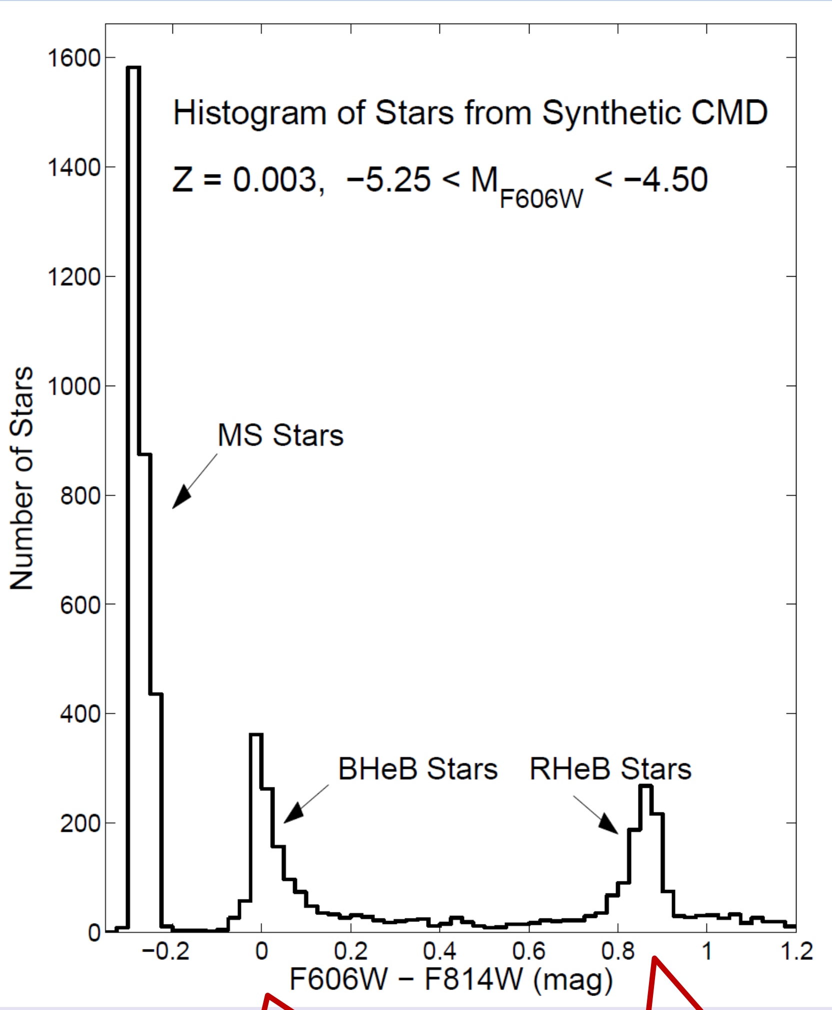
Observations of massive stars: Main, Blue and Red Sequences



Simulations of evolution in H-R diagram of stars with solar metallicity, from main sequence to end of He-burning. [MESA]

Most of the star life-time is spent in one of the three sequences: the **Main Sequence** (central H-burning), the **Red** central **He-Burning** sequence, and the **Blue** central **He-Burning** sequence

Observable evolutionary Phases: Central H- and He-burning



Log T[k]=4

Log T[k]=3.7

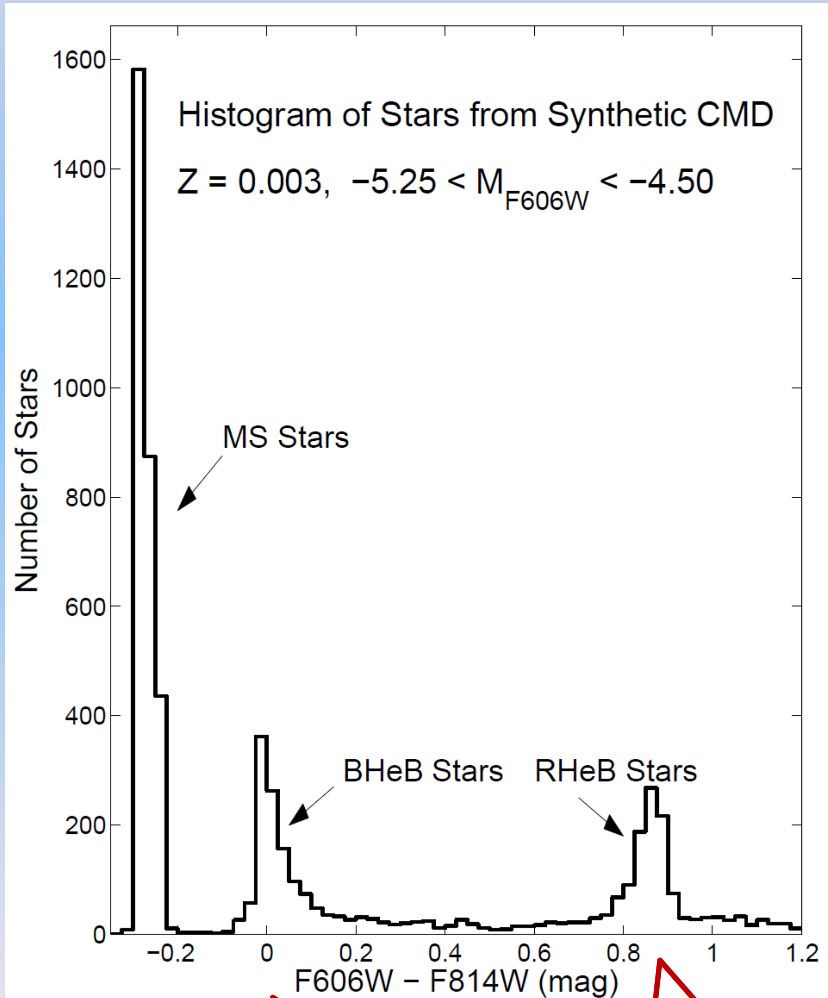
Blue stars have been observed for many decades and measurements are very accurate.

The contamination from MS stars transitioning to BHeB is conservatively estimated to be less than 10% (Dohm-Palmer & Skillman 2002).

The complete disappearance of all blue stars in certain luminosity regions is physically unacceptable.

From Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

Observable evolutionary Phases: Central H- and He-burning



Log T[k]=4

Log T[k]=3.7

Result:

A value of g_{10} above 0.8 would be incompatible with the current observations of HeB sequences.

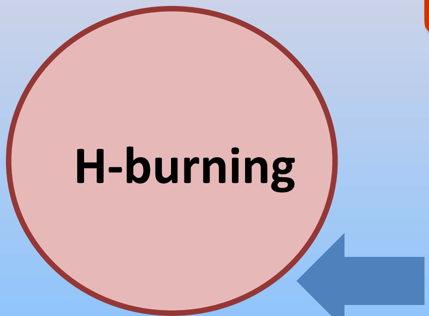
This analysis provides the *strongest bound to date* on the axion-photon coupling.

A.Friedland, M.G., and M.Wise,
Phys. Rev. Lett. 110, 061101 (2013)

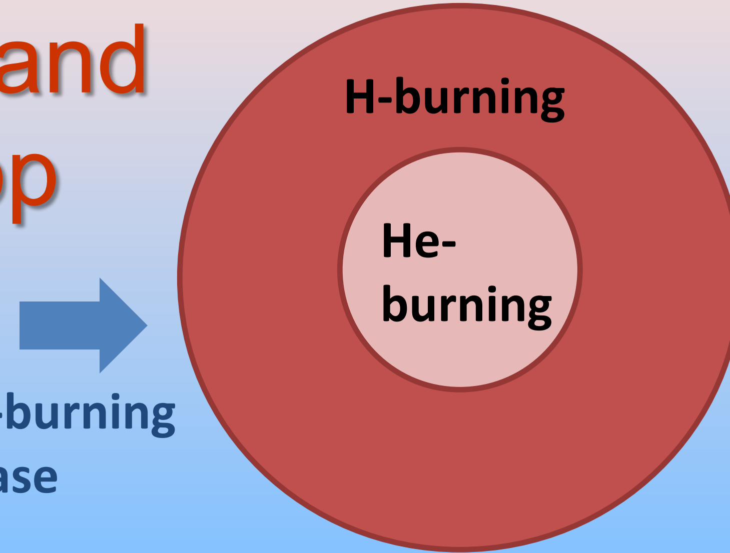
See also
G. Raffelt, **http://physics.aps.org/articles/v6/14**

Astrophys.J. 740 (2011)

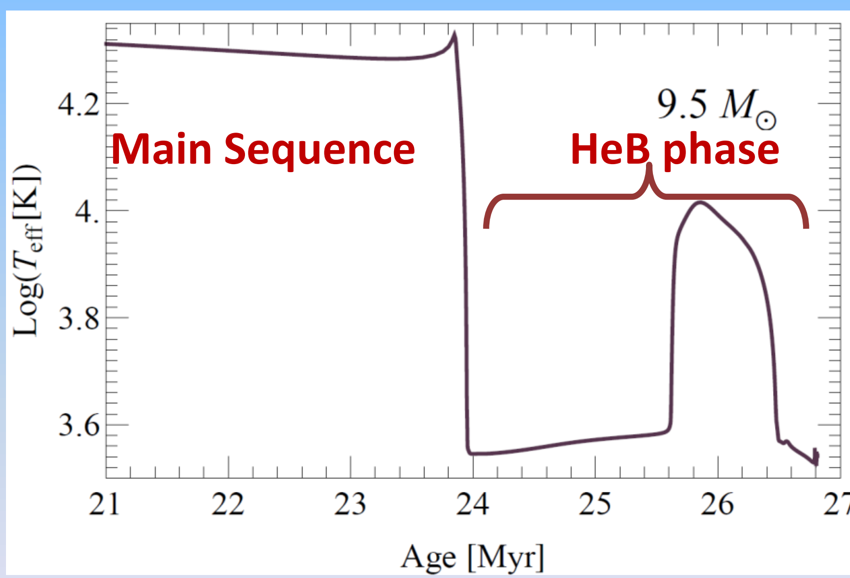
Massive stars and the Blue Loop

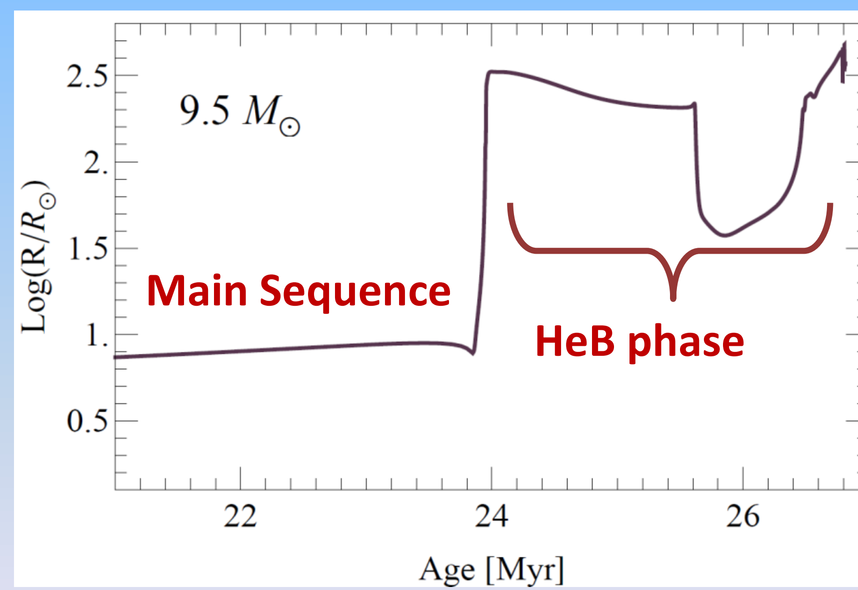


H-burning phase (Main Sequence)



He-burning phase





Simulations for a 9.5$M_\odot$, solar metallicity, from main sequence to end of He-burning.

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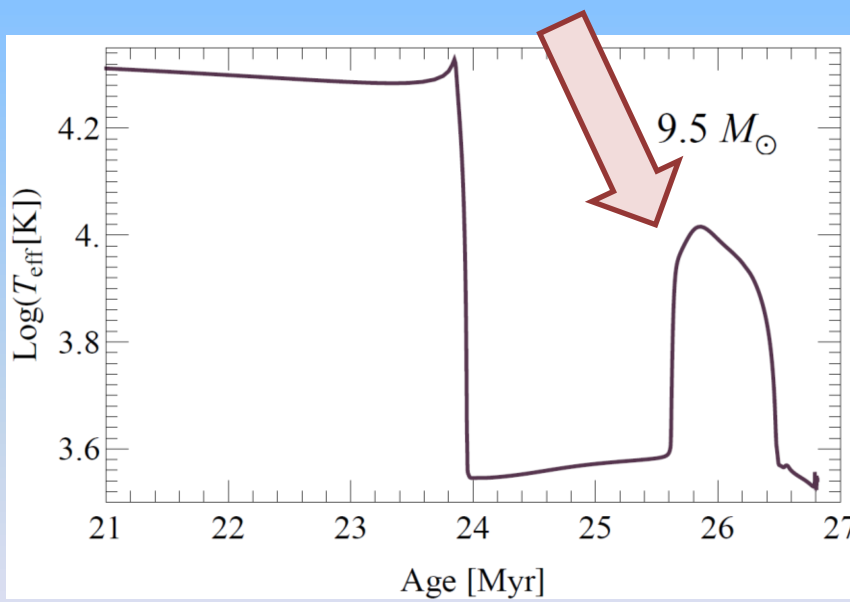
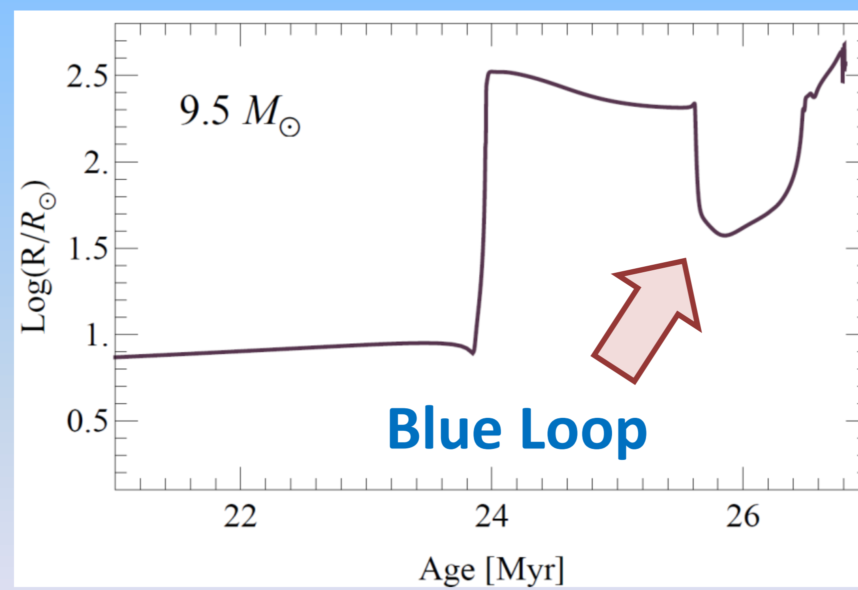
The Blue Loop

The journey of the star toward the hotter regions and back is called the **blue loop**. It happens for stars of a few solar masses during the He-burning stage.

Blue Loop





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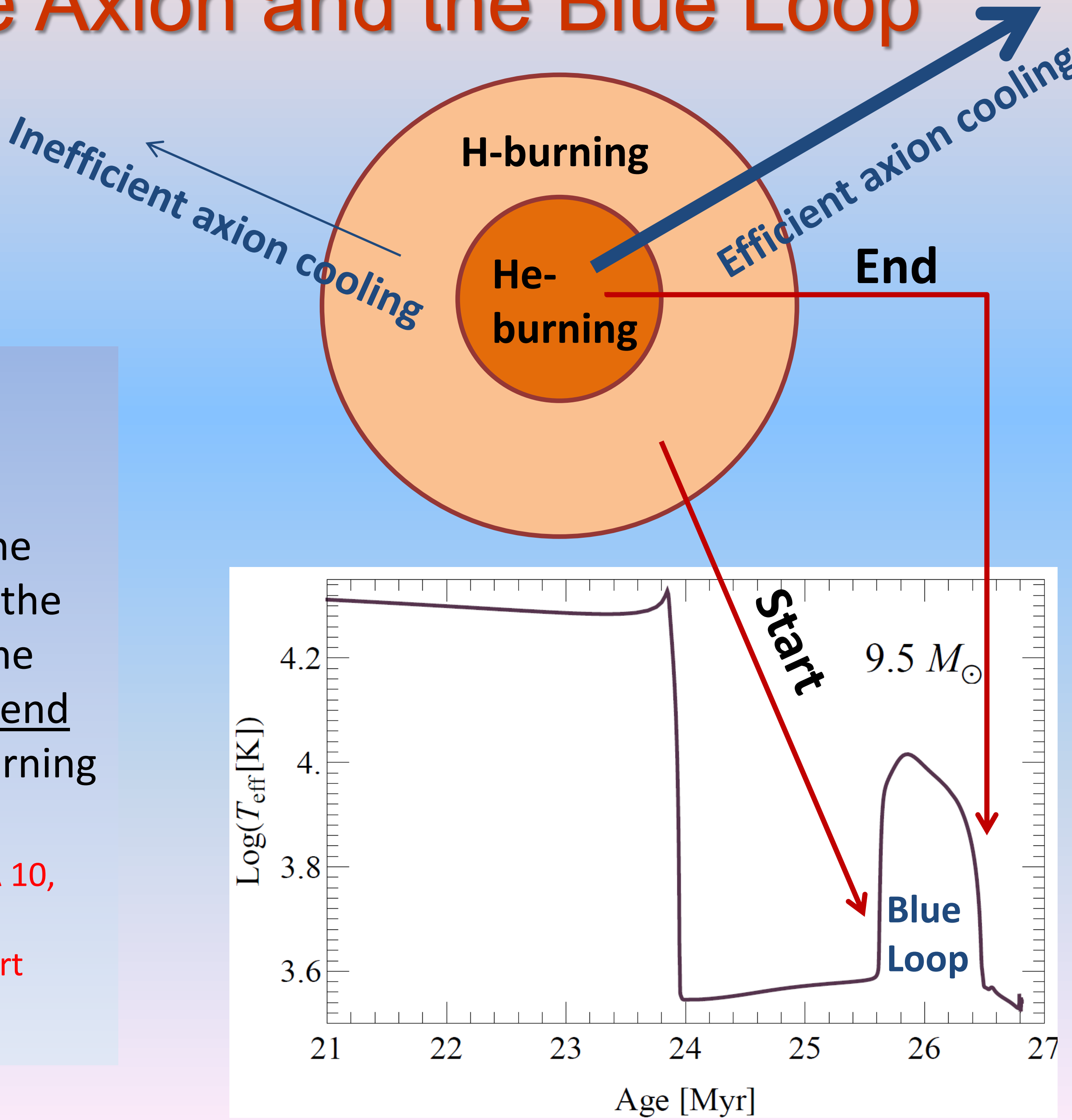
The Axion and the Blue Loop

Blue Loop:

the <u>beginning</u> of the blue loop is set by the H-burning shell time scale whereas the <u>end</u> is set by the He-burning core time scale

[Lauterborn et al., A&A 10, (1971), Kippenhahn and Weigert (1994)]



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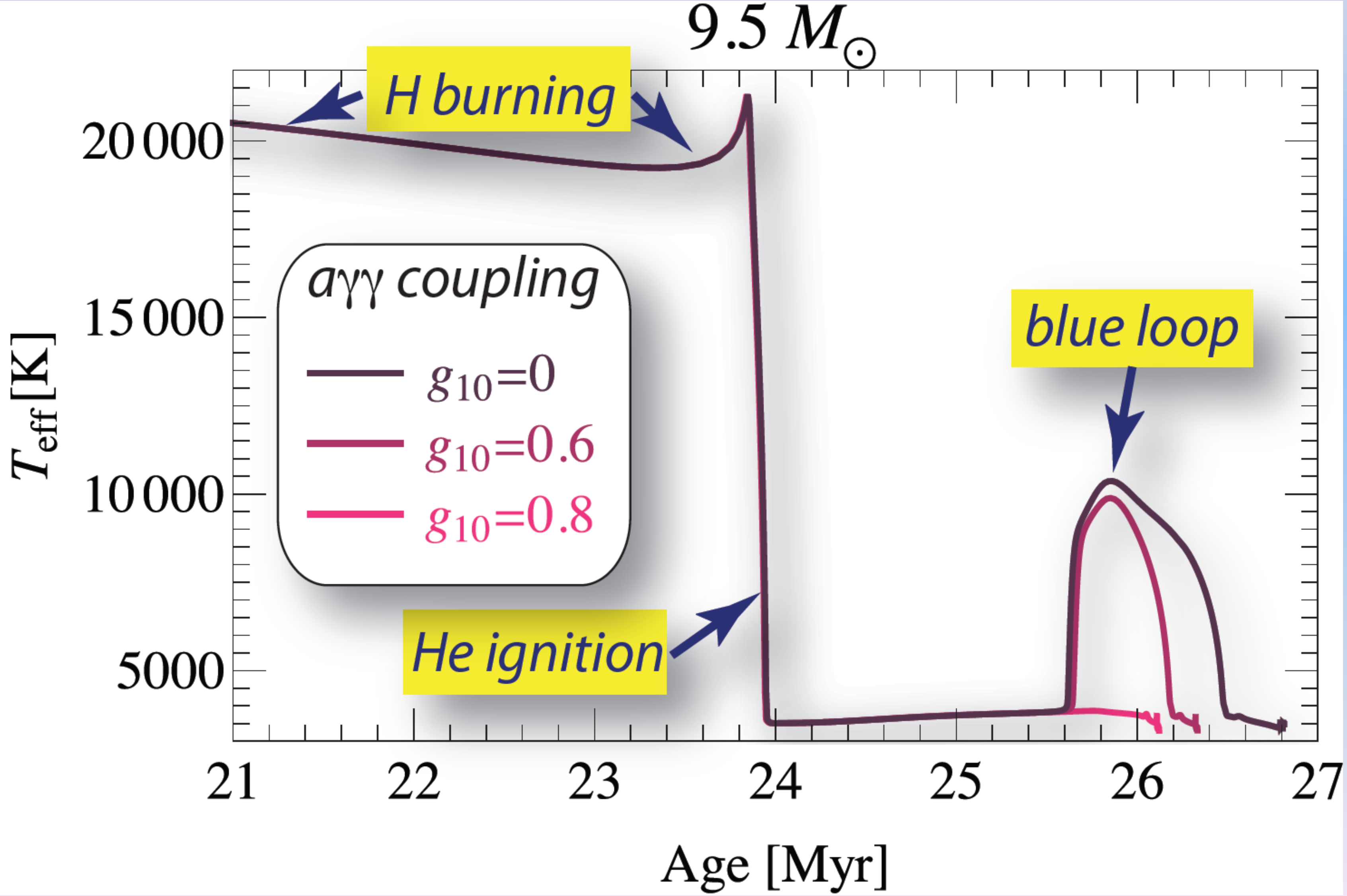
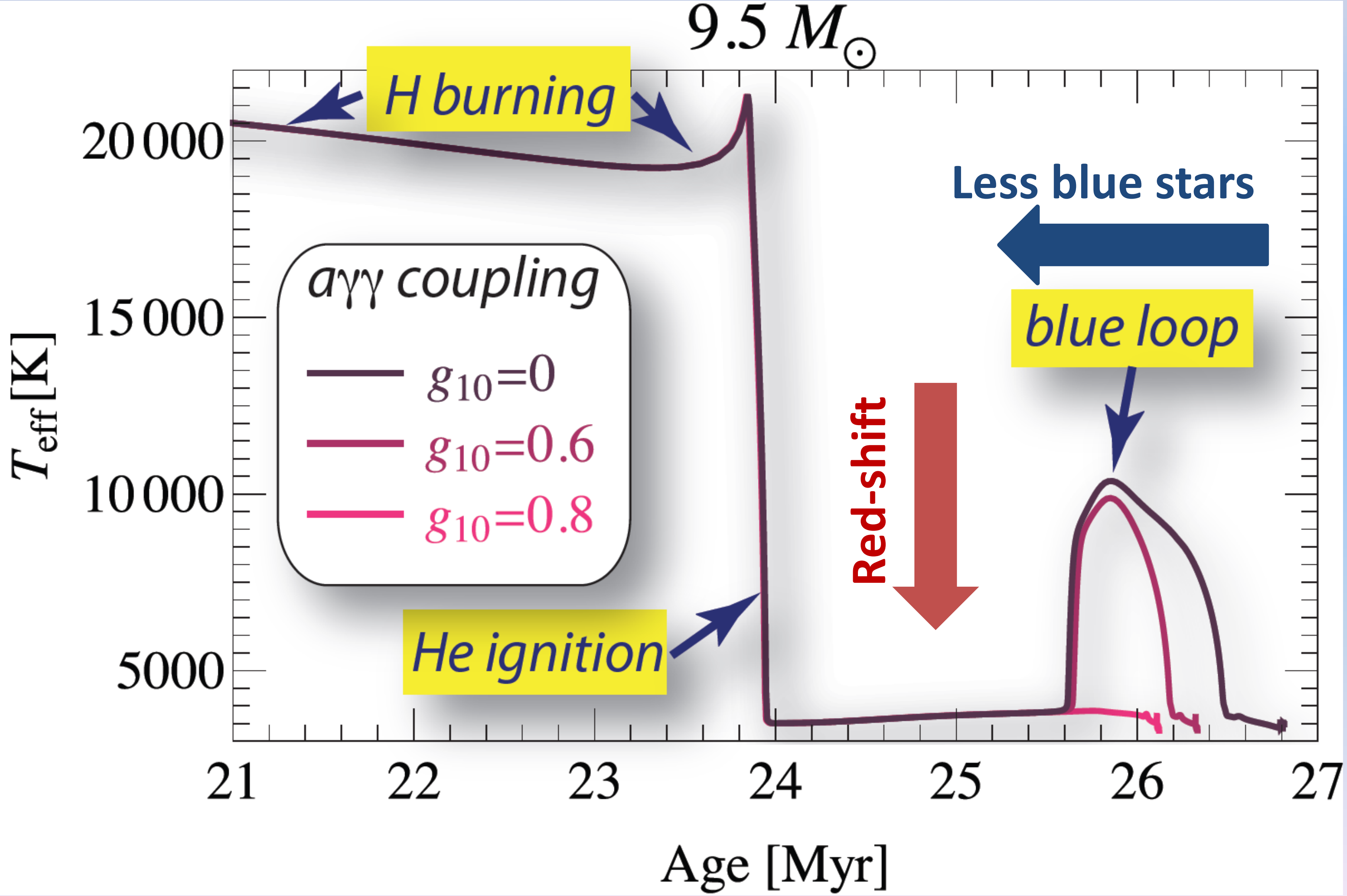


A.Friedland, M.G., and M.Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

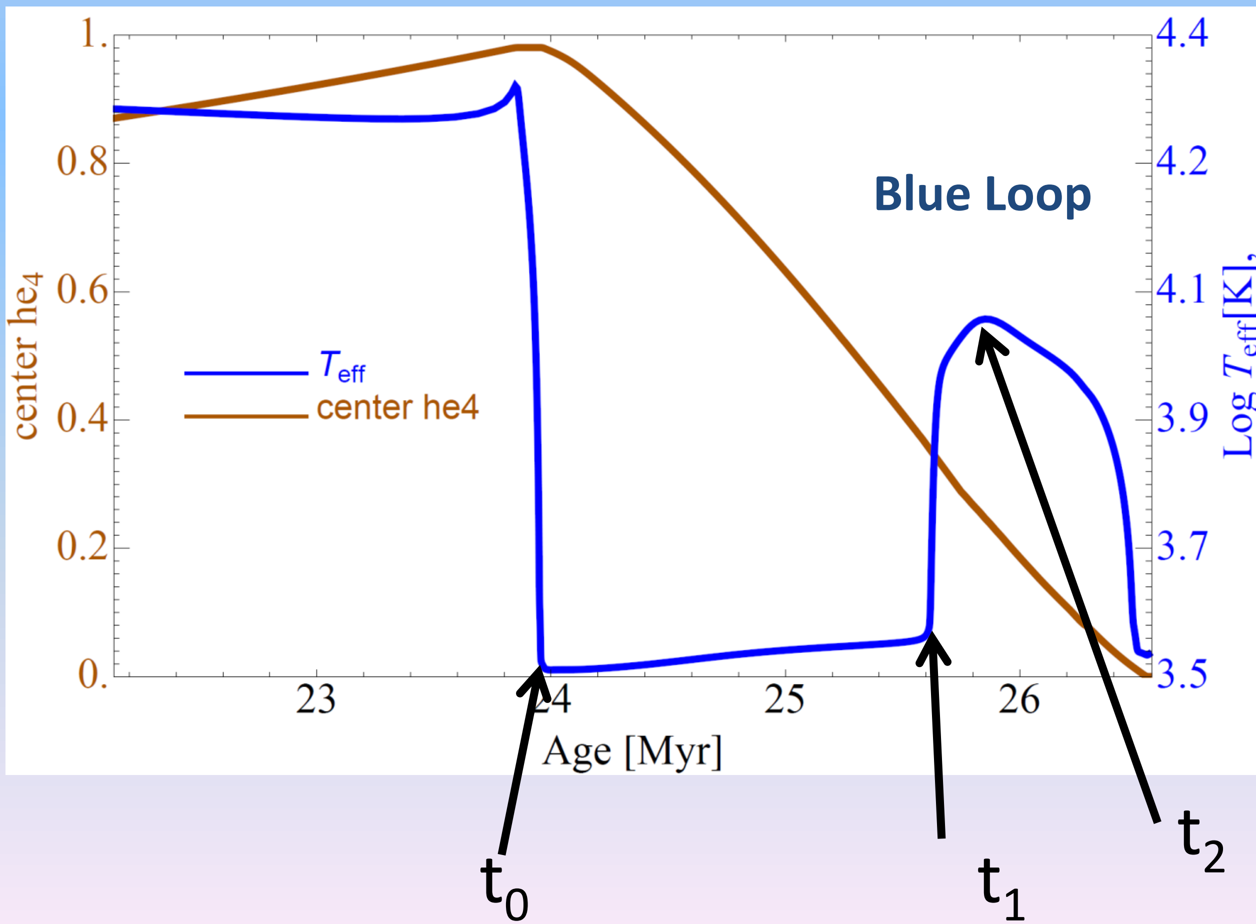
The Axion and the Blue Loop



A.Friedland, M.G., and M.Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Blue loop as a probe for Fundamental Physics

When the He content in the core reaches a certain lower value (t_2), the surface temperature stops increasing and goes back to the red region of the HR diagram.
Speeding up the core evolution would eliminate the blue loop phase
[Lauterborn et al., A&A 10, (1971), E. Hofmeister, Z.F.A. 67, (1967)]



Characteristic times:

t_0: beginning of the core *He-burning phase*

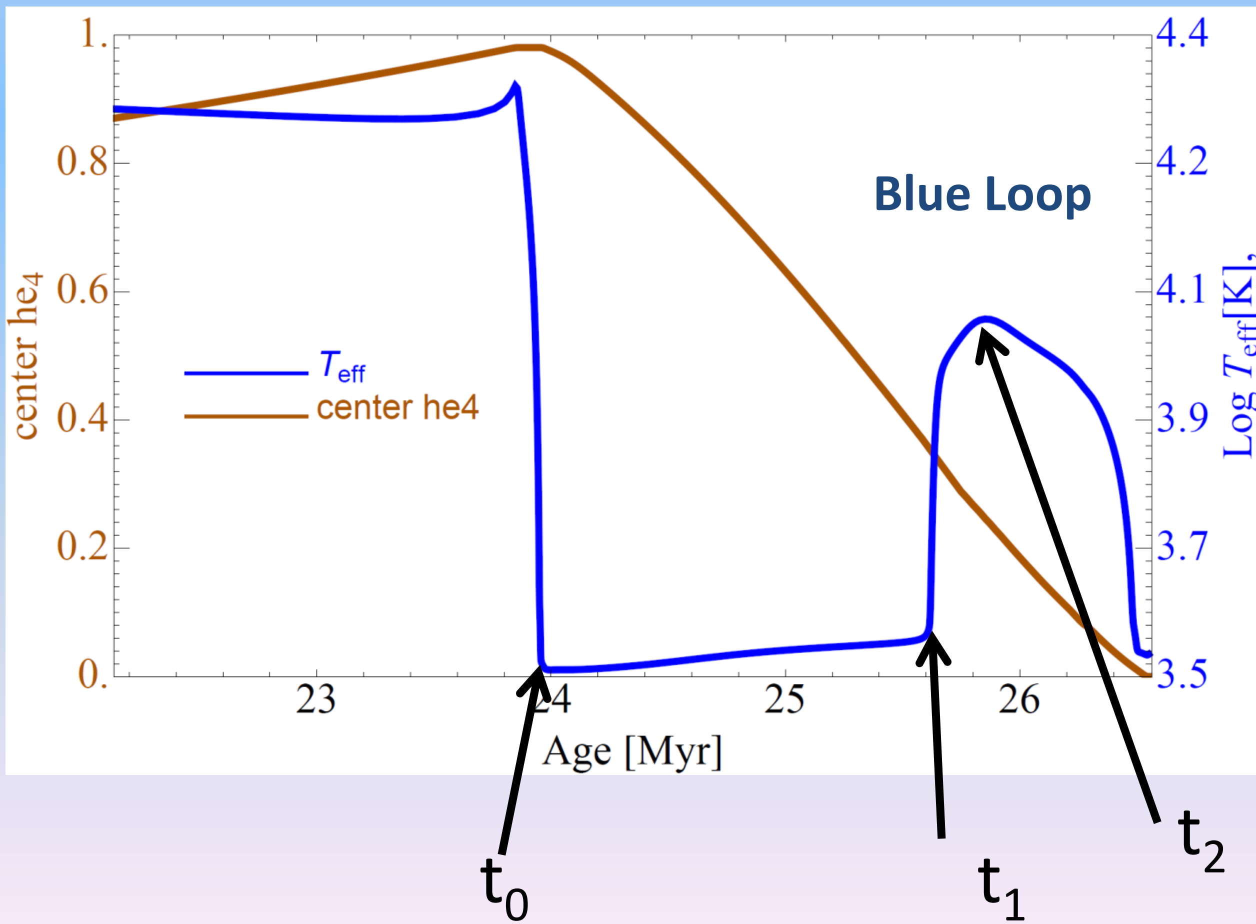
t_1: beginning of the *blue loop phase*

t_2: *turning point*

Blue loop as a probe for Fundamental Physics

A possible criteria: *A novel cooling mechanism which changes the he-burning time from t_{He} to t'_{He} would eliminate the blue loop phase if:*

$$\boxed{\frac{t'_{He}}{t_{He}} \leq \frac{t_1 - t_0}{t_2 - t_0}}$$



This criteria is independent from convection prescriptions and other possible uncertainties.

A conservative requirement for stars around 9-11 $M_\odot$ is that

$$\boxed{t'_{He}/t_{He} \leq 0.8}$$

is not allowed by observations.

Astro Labs: Massive vs. HB stars

HB and massive stars offer two different criteria for probing exotic processes which are efficient during the He-burning stage:

HB stars:	Massive stars:
Lower core temperature, higher core density;	Higher core temperature, lower core density;
Relatively low energy production during he-burning:	High energy production during he-burning:
$\boxed{\varepsilon_x \approx \text{a few } 10 \text{ ergs g}^{-1}\text{ s}^{-1}}$	$\boxed{\varepsilon_x \approx \text{a few } 10^3 \text{ ergs g}^{-1}\text{s}^{-1}}$
Observations require:	Observations require:
$\boxed{t'_{He}/t_{He} \geq 0.7}$	$\boxed{t'_{He}/t_{He} \geq 0.8}$

[cfr. PDG and G.Raffelt in Axions, Springer (2010), chapter 3]

Astro Labs: Massive vs. HB stars

HB and massive stars offer two different criteria for probing exotic processes which are efficient during the He-burning stage:

HB stars:

Low
high

Rela
proc
burn

$\varepsilon_x \approx$

Observations req

$$t'_{He}/t_{He} \geq 0.7$$

[cfr. PDG and G.Raffelt in Axions, Springer (2010), chapter 3]

Massive stars:

$$t'_{He}/t_{He} \geq 0.8$$

The case of axion is particularly interesting since the axion energy production rate seems to be fairly independent on the initial star mass at least for our mass range [Friedland, M.G., Wise, (2013)] and approximately given by:

$$\frac{t'_{He}}{t_{He}} \approx \frac{1}{1+0.4\, g_{10}^{2}}$$

So, the criteria below give the correct bounds g_{10}=1 from low HB stars and g_{10}=0.8 from massive stars.

Astro Labs: Massive vs. HB stars

HB and massive stars offer two different criteria for probing exotic processes which are efficient during the He-burning stage:

HB stars:

Lower core temperature, higher core density;

Relatively low energy production during he-burning:

$$\boxed{\varepsilon_x \approx \text{a few } 10 \text{ ergs g}^{-1}\text{ s}^{-1}}$$

Observations require:

$$\boxed{t'_{He}/t_{He} \geq 0.7}$$

[cfr. PDG and G.Raffelt in Axions, Springer (2010), chapter 3]

Massive stars:

Higher core temperature, lower core density;

High energy production during he-burning:

$$\boxed{\varepsilon_x \approx \text{a few } 10^3 \text{ ergs g}^{-1}\text{s}^{-1}}$$

Observations require:

$$\boxed{t'_{He}/t_{He} \geq 0.8}$$

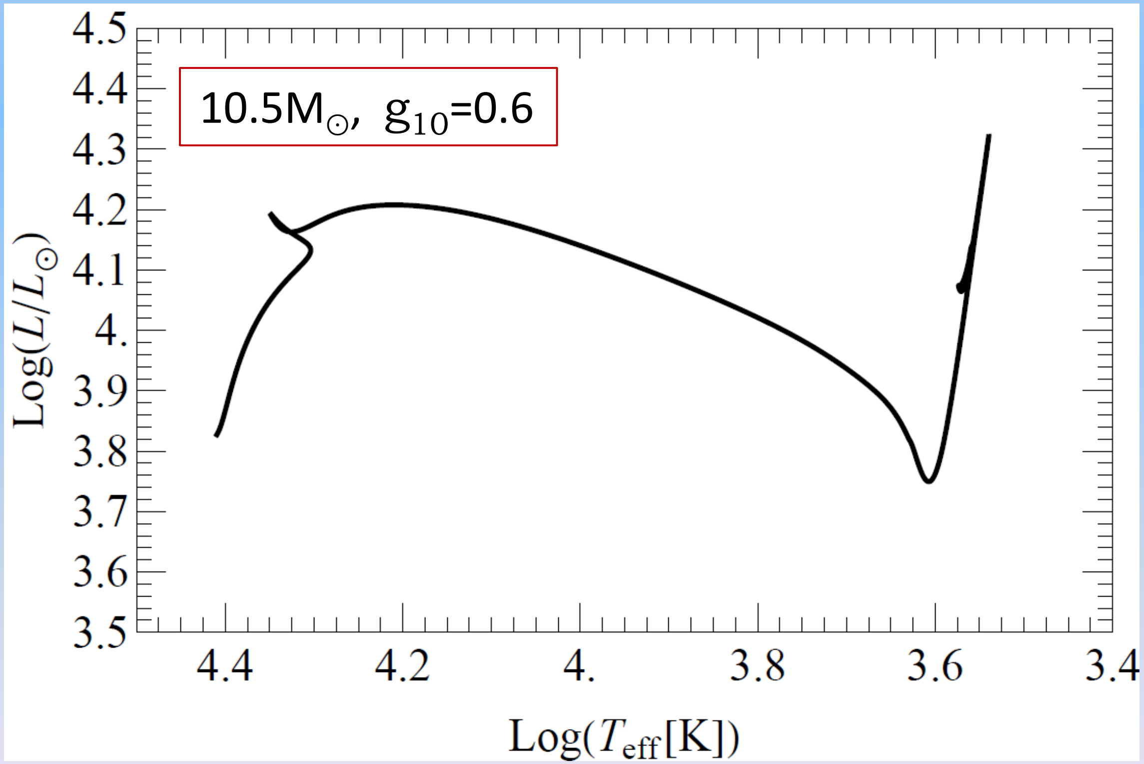
Massive stars are hotter and less dense. The maximal exotic cooling allowed by observation is larger than HB stars.

Exotic processes which are very sensitive to temperature are likely to be constrained more efficiently from massive stars. Otherwise, HB stars offer a better lab

Can we do better?

Can we do better?

Some kind of stars show a stronger response than other to axion cooling. [Friedland, M.G., Wise, in preparation].

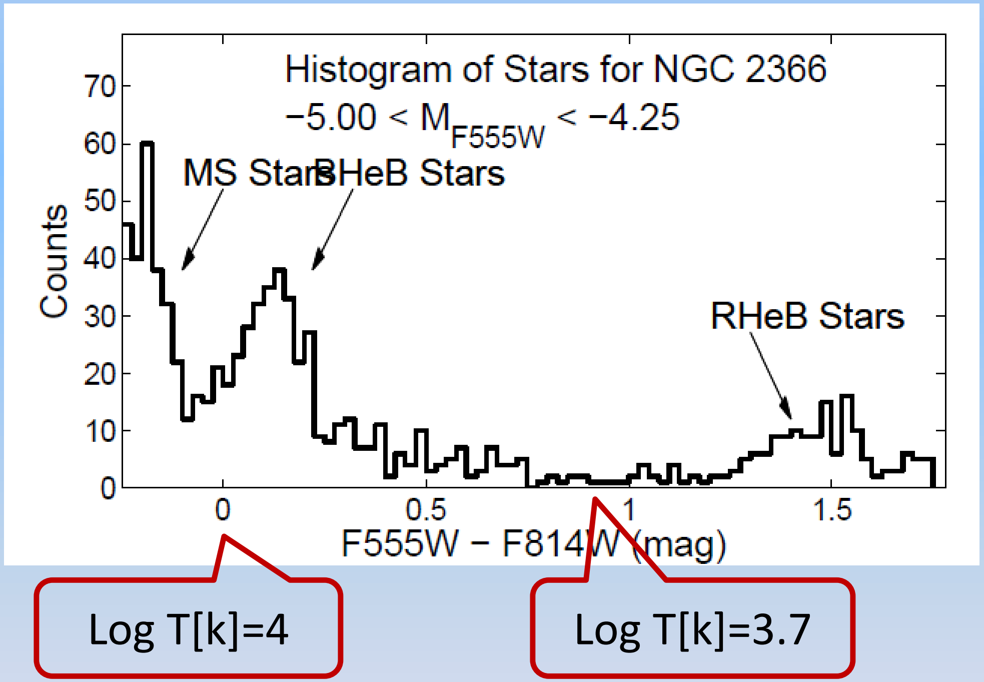


In the case of stars of mass above 10 $M_\odot$ or so, the blue loop stage disappears already for g_{10}=0.6.

Stars of even larger mass are somewhat harder to model [M. El Eid (1995)]

Can we do better?

In addition, counting stars is improving considerably. Being able to count accurately allows to set a better bounds



Kristen B. W. McQuinn et. Al. (2011): Histograms of the stars in the dwarf galaxy NGC 2366

In fact, the requirement that we used to derive the g_{10}=0.8 bound is <u>conservative</u>.

Given accurate counts, it may be possible to check whether the number of stars in the blue loop phase is reduced.

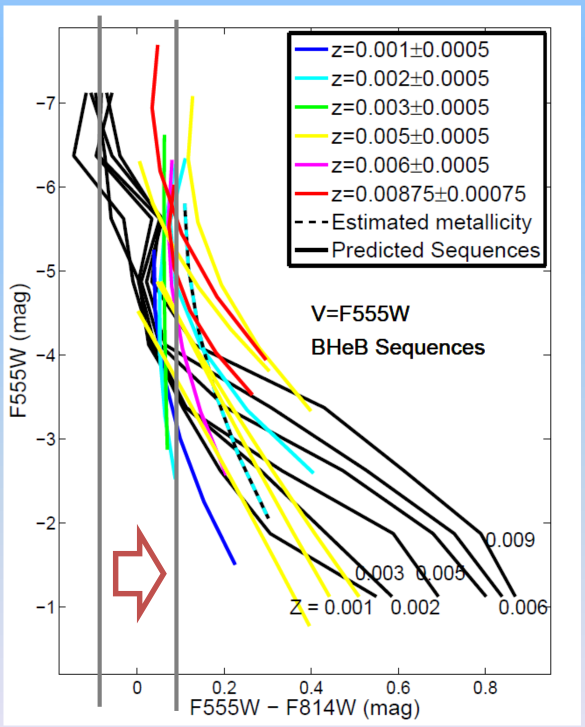
For example, g_{10} = 0.6 would reduce the time a 9.5 $M_\odot$ star spends on the blue loop by a factor of two or so. To get the same sensitivity for g_{10} from solar-mass stars requires knowing the numbers of HB stars to a 10% precision.

Two astrophysical puzzles: a hint to new physics?

Current observations show:

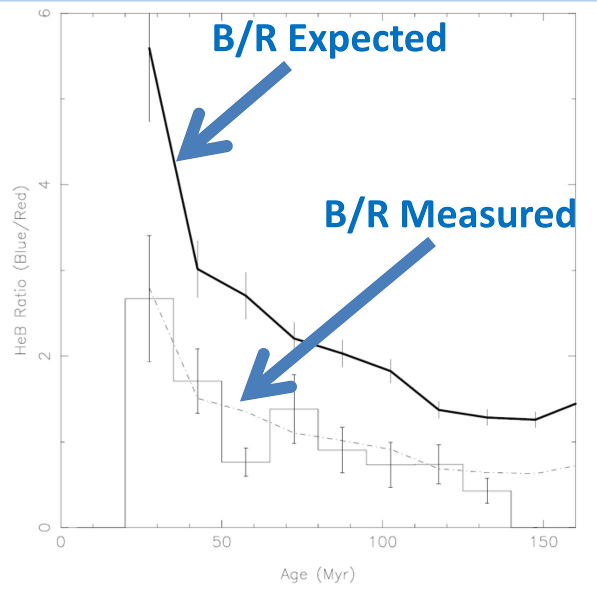
1) a small red-shift of the bluest point of the blue loop in the high luminosity region of the CMD and

2) too many blue stars (B/R problem).



V-I Color

Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)



R. C. Dohm-Palmer and E. D. Skillman, The Astronomical Journal, 123 (2002)

From Palmer, Skillman (2002): *"Note how well the functional form of the observations matches that of the model. However, the model values are twice as large as the observations."*

A solid understanding of the evolutionary model parameters may help reduce or eliminate these long-standing puzzles.

If a careful analysis of the standard astrophysics uncertainties were to be insufficient, this could be an hint to new physics.

We notice, in fact, that an axion-photon coupling a little below the current bound would reduce both problems.

Conclusions

- Low and intermediate mass stars offer good laboratories to study models of light, weakly interacting particles.

- Axions have a strong impact on the evolution of low and intermediate mass stars during the core He-burning stage.

- Massive stars offer an efficient novel probe to test new physics. For the axion-photon coupling they provide the constraint g_{10}=0.8 (up to m_a<40 keV or so) which is the best bound to date on this coupling.

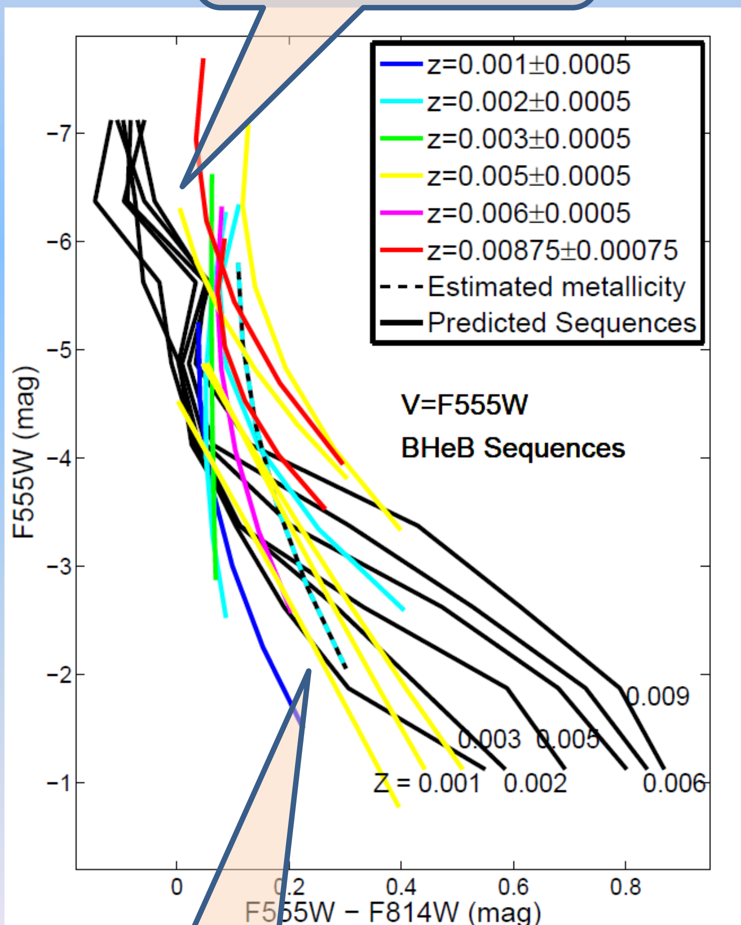
- A thorough analysis of independent observations and comparisons with the evolutionary models of massive stars could help our understanding of particle physics, in particular of the axion, improve bounds and possibly discover hints to new physics.

Thank

You

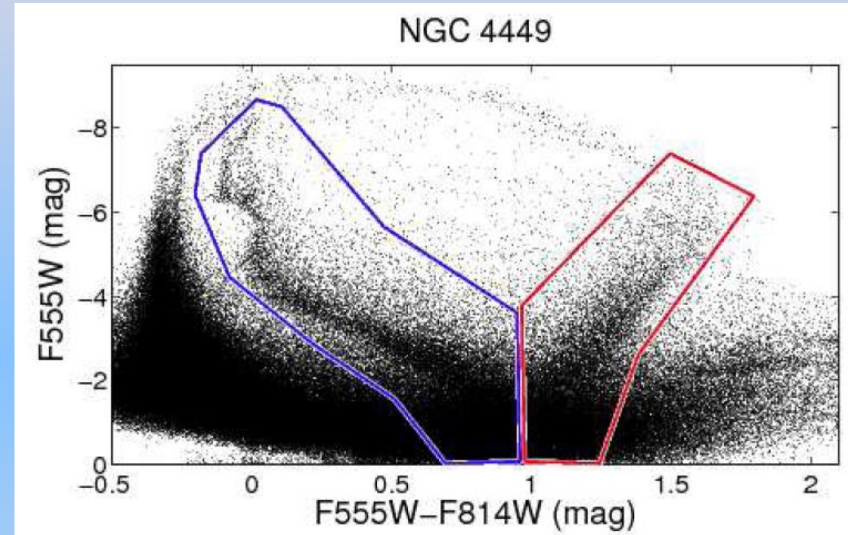
Experimental Evidence for Blue Sequences

High mass
(young cluster)

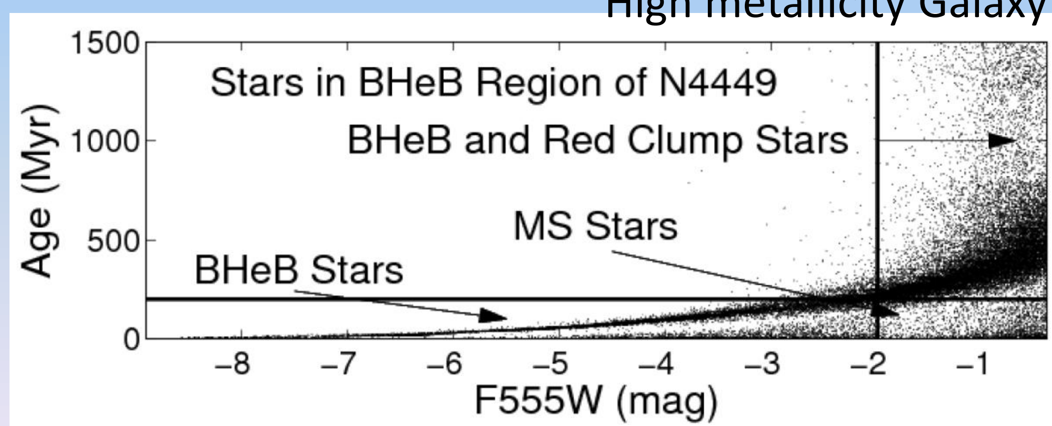


Low mass
(old cluster)

V-I Color

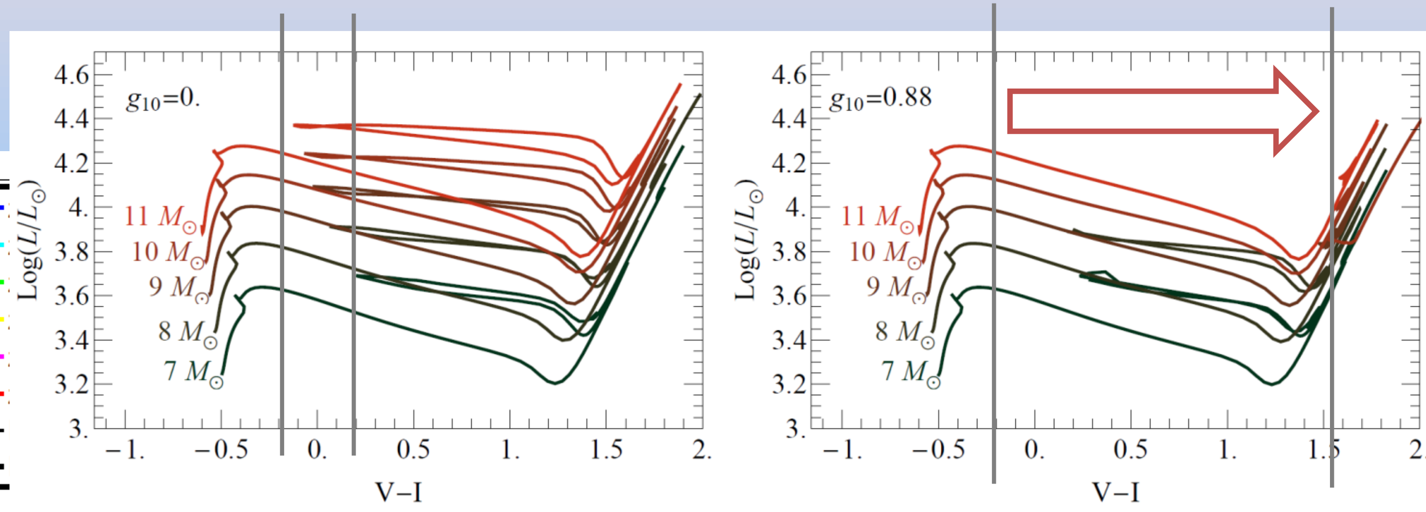


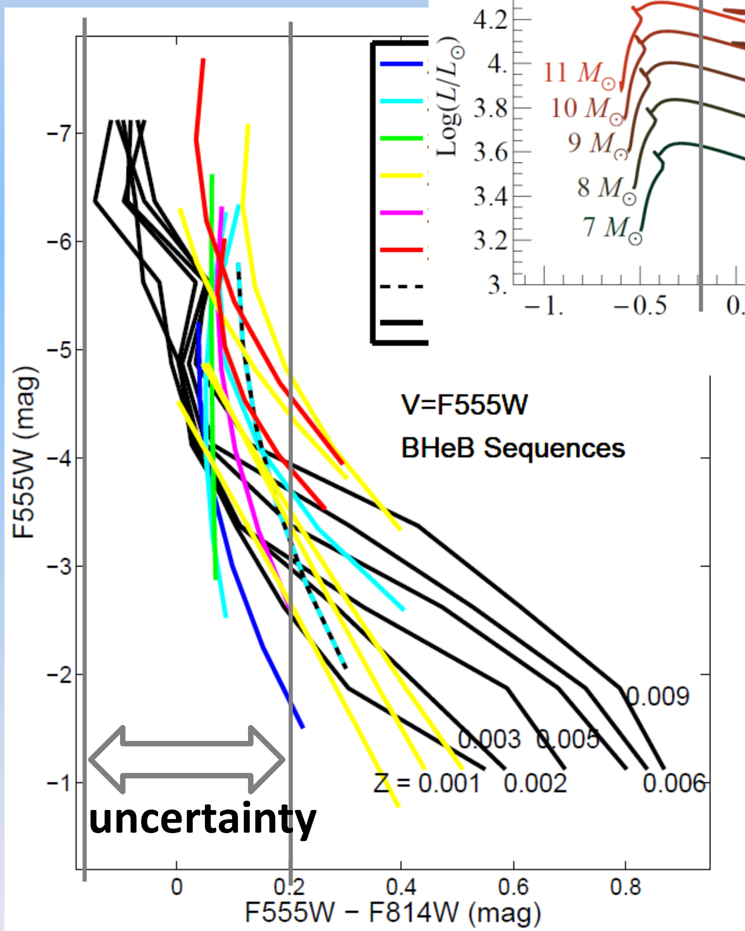
High metallicity Galaxy



Figures from Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

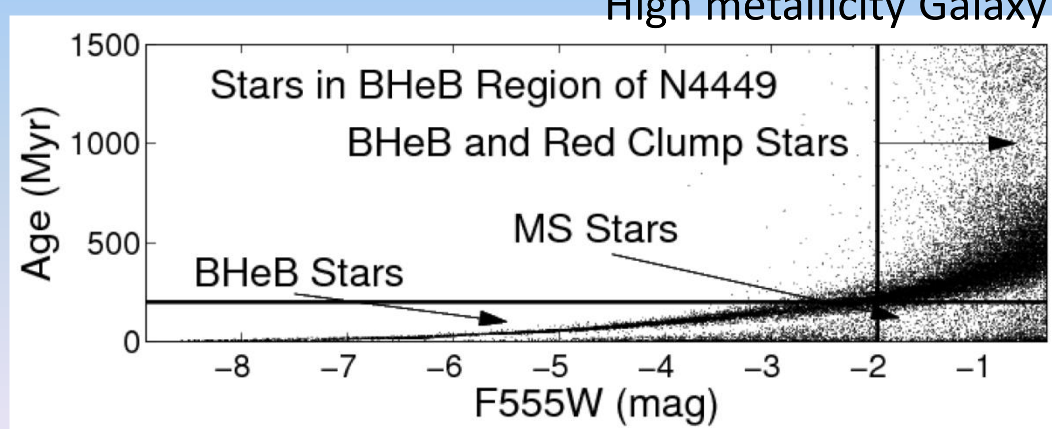
Experimental Evidence for Blue Sequences





V-I Color

High metallicity Galaxy



Figures from Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)